Supermassive black holes and strong gravity with Constellation-X

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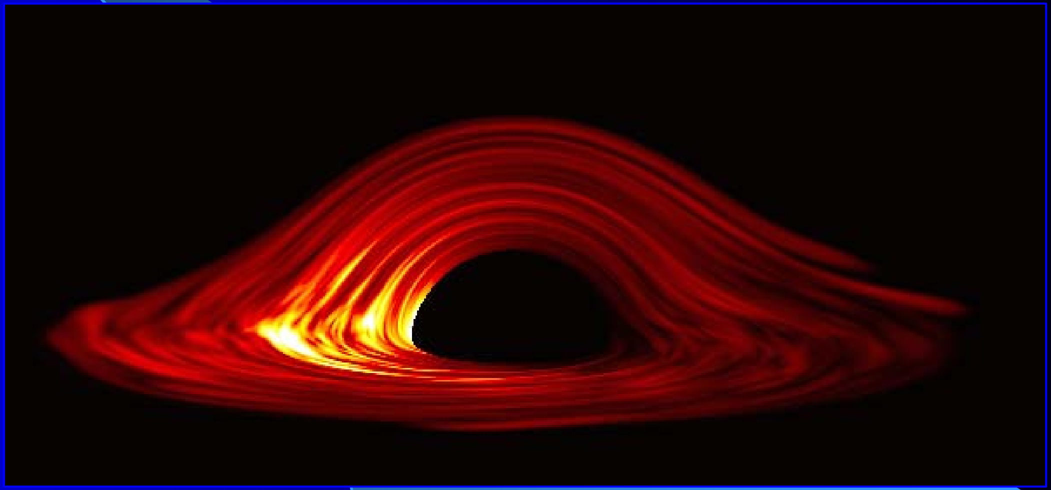


The black-hole/strong-gravity team

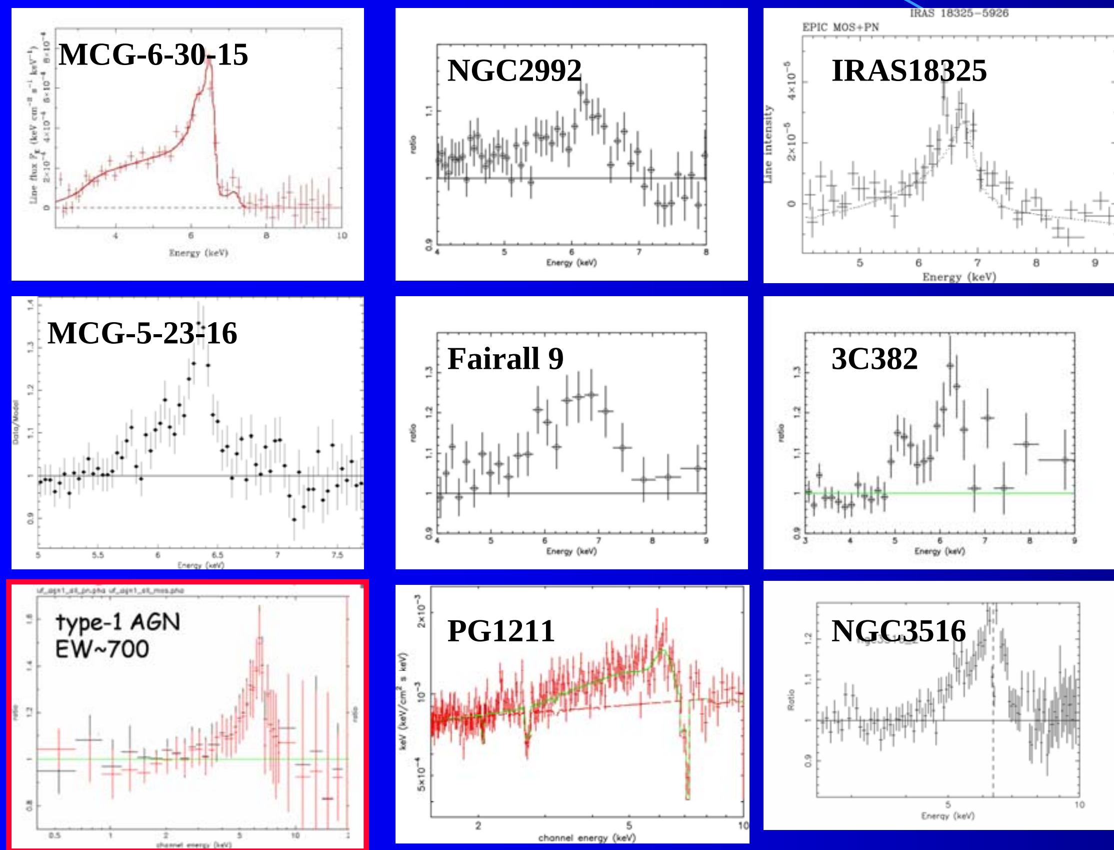
- Chris Reynolds - team lead
- Mitch Begelman
- Andy Fabian
- Jon Miller
- James Reeves (next talk)
- Tod Strohmayer
- Kim Weaver

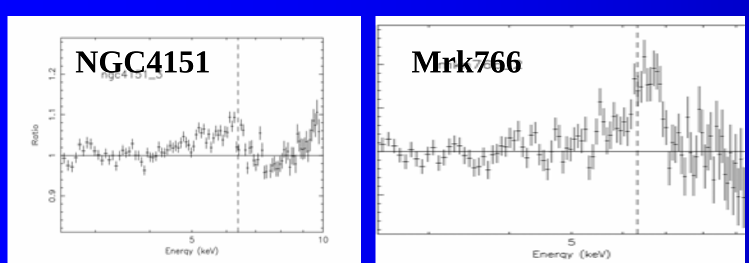
- Also stay tuned for Jane Turner’s talk

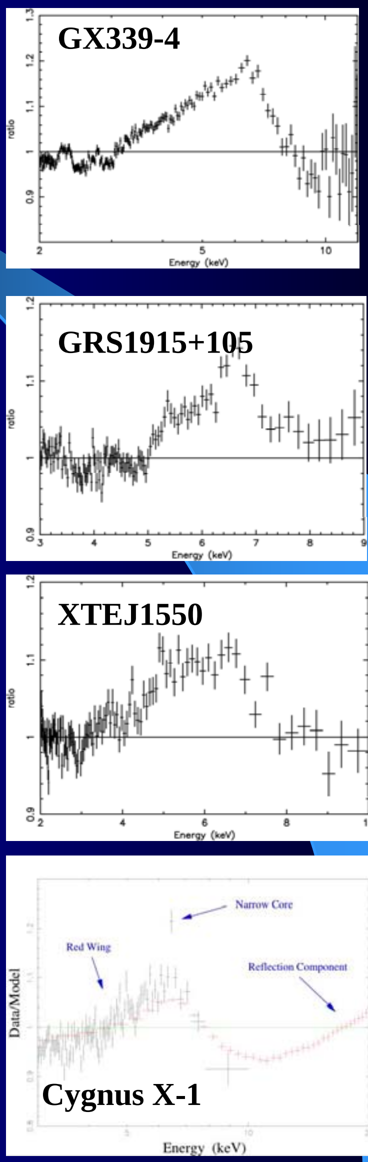
Outline

- The continued importance of broad iron lines
- Probing strong gravity
  - Detailed study of constraints from orbital timescale iron line variability
  - Scheme for searching from deviations from GR
- Black hole spins
  - Measuring spins from time-averaged broad iron lines
  - Estimates for number of sources measurable
- Spanning the mass scale of black holes

Re-affirmed importance of broad iron lines



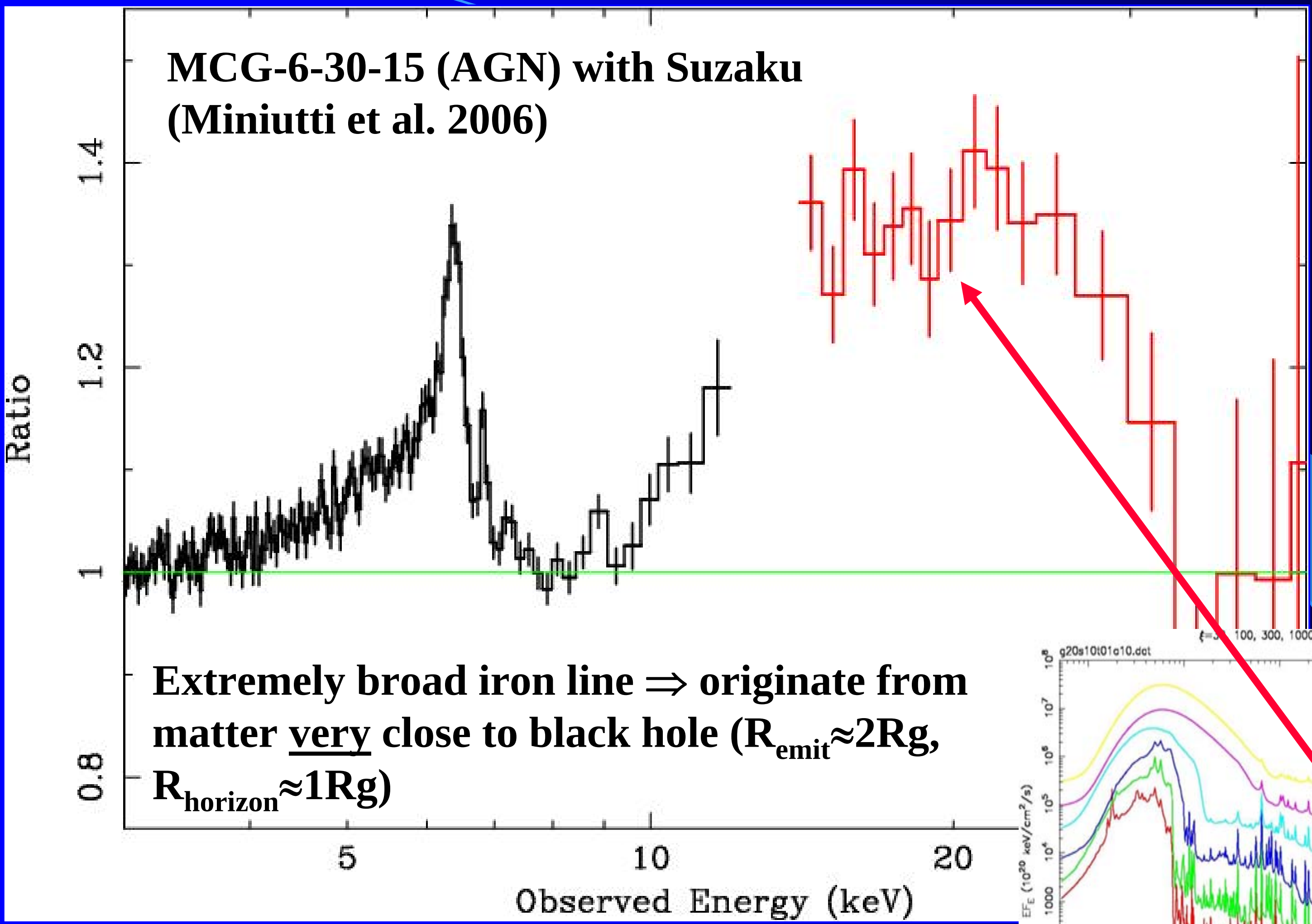


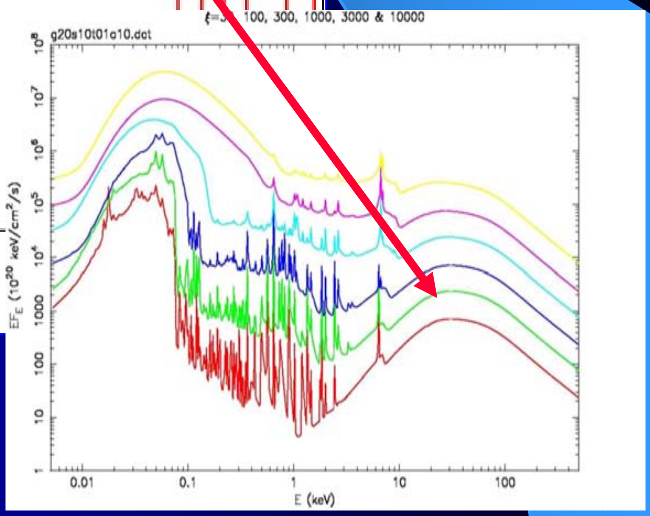


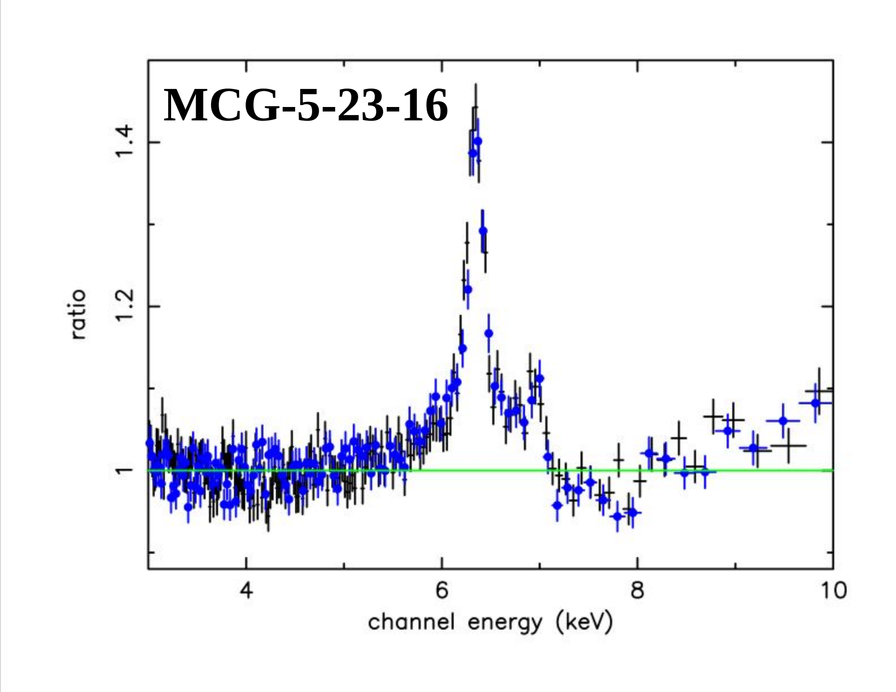
Similar line profiles from stellar-mass and super-massive black hole systems… demonstrates insensitivity of line profile to mass

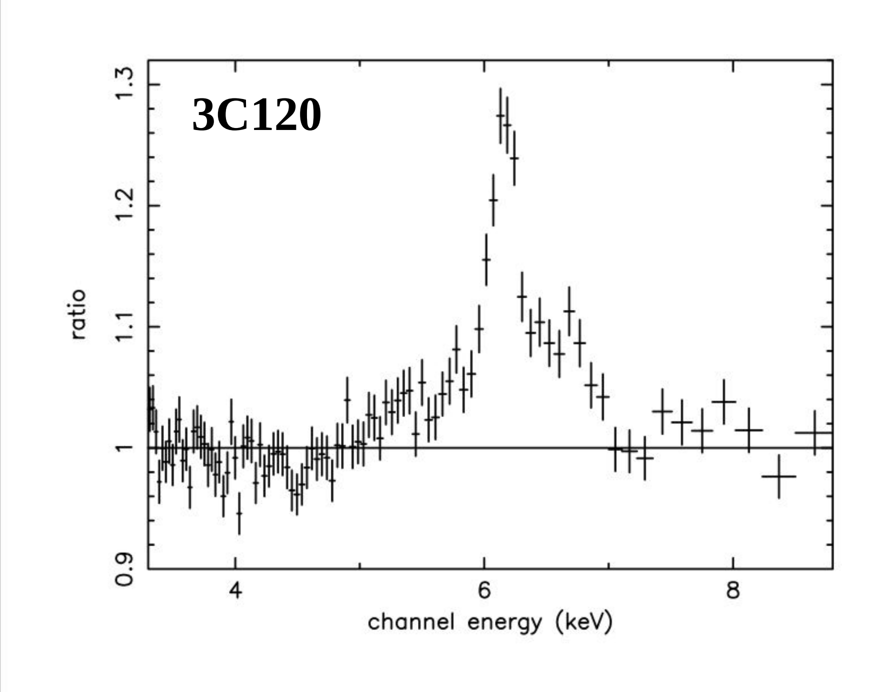
MCG-6-30-15 (AGN) with Suzaku
(Miniutti et al. 2006)

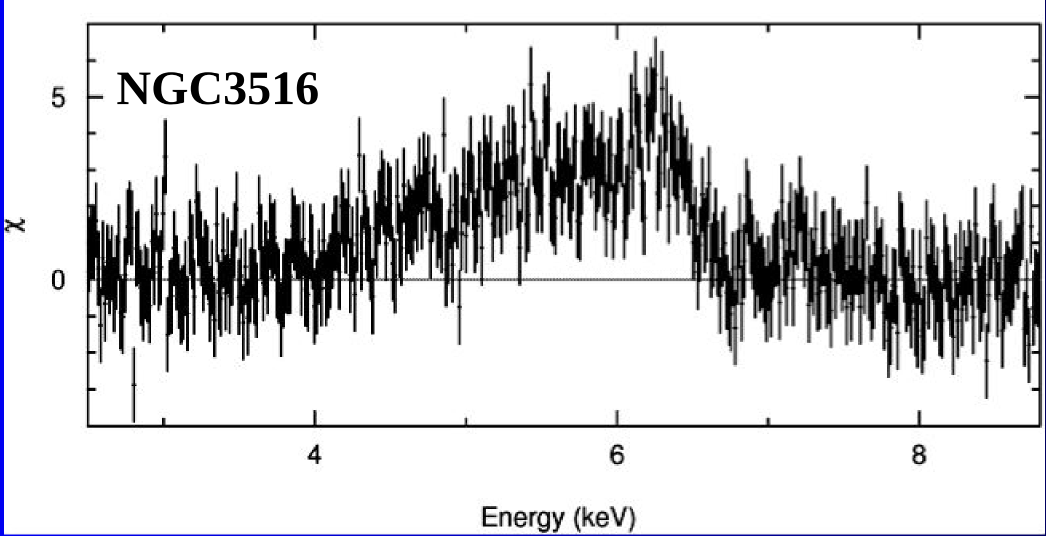
Extremely broad iron line ⇒ originate from matter <u>very</u> close to black hole ($R_{emit} \approx 2Rg$, $R_{horizon} \approx 1Rg$)











Other Suzaku results (from review by J.Reeves)

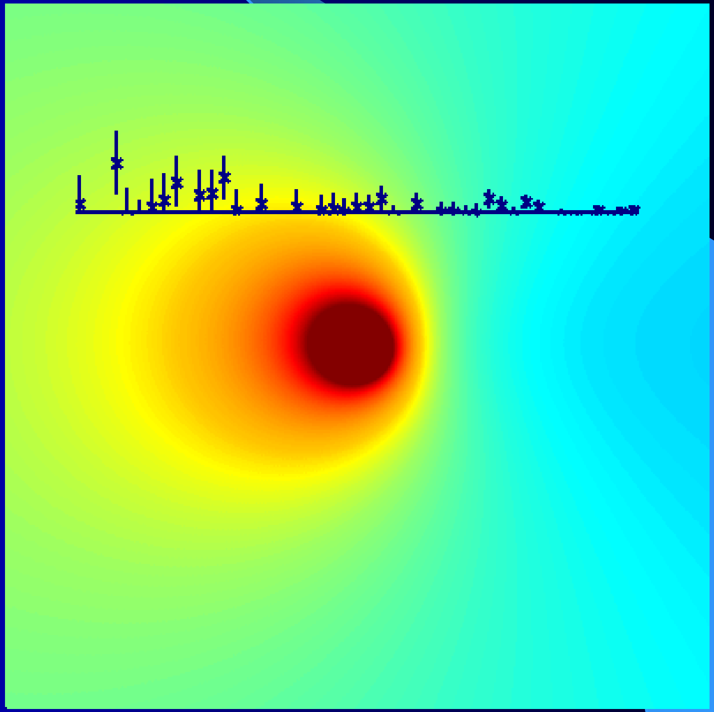
I : Probing Strong Gravity: Rapid iron line variability

- Current broad iron line studies already provide qualitative test of GR!
  - Confirm strong gravitational redshifts close to BH
  - Confirm relativistic velocities close to BH
- But spacetime metric is encoded in radial dependence of V and z… time averaged line profiles do not contain enough information to probe this!
- Enter line variability…

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Iron line profiles changes in response to the echo of a rapid X-ray flare across the disk surface

“Relativistic iron line reverberation”

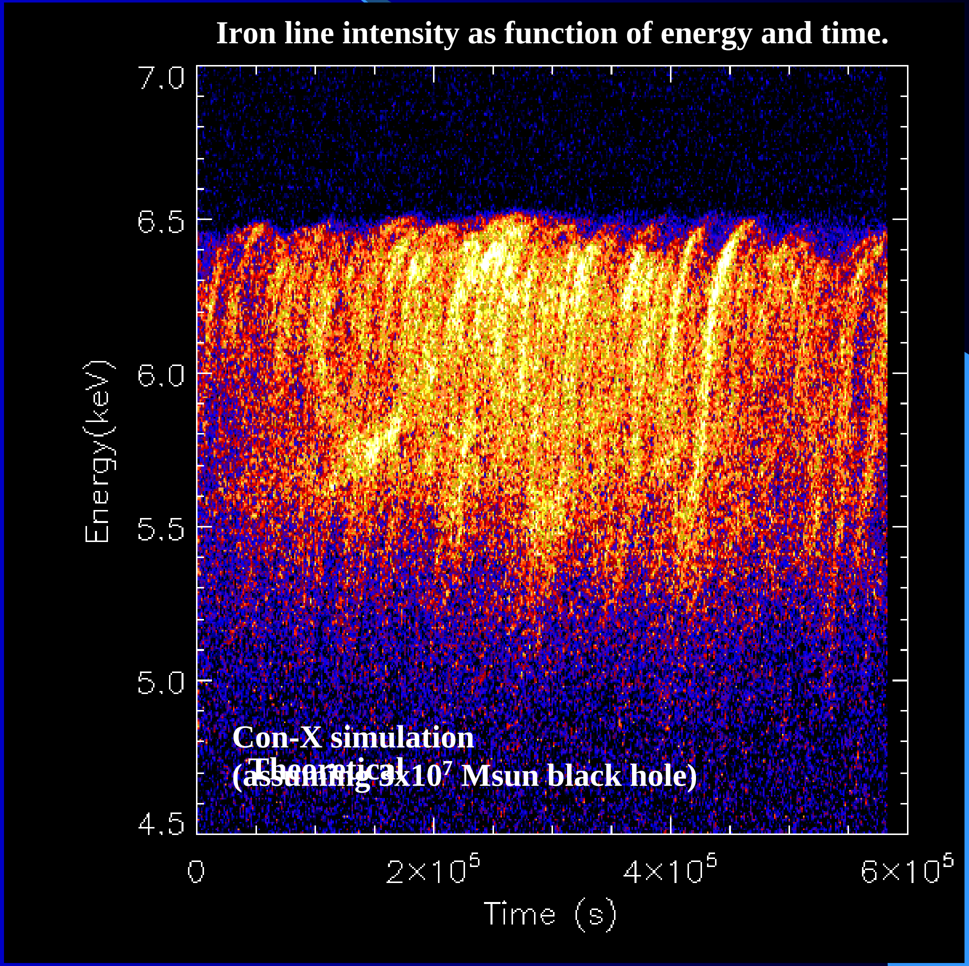


Reynolds et al. (1999)
Young & Reynolds (2000)

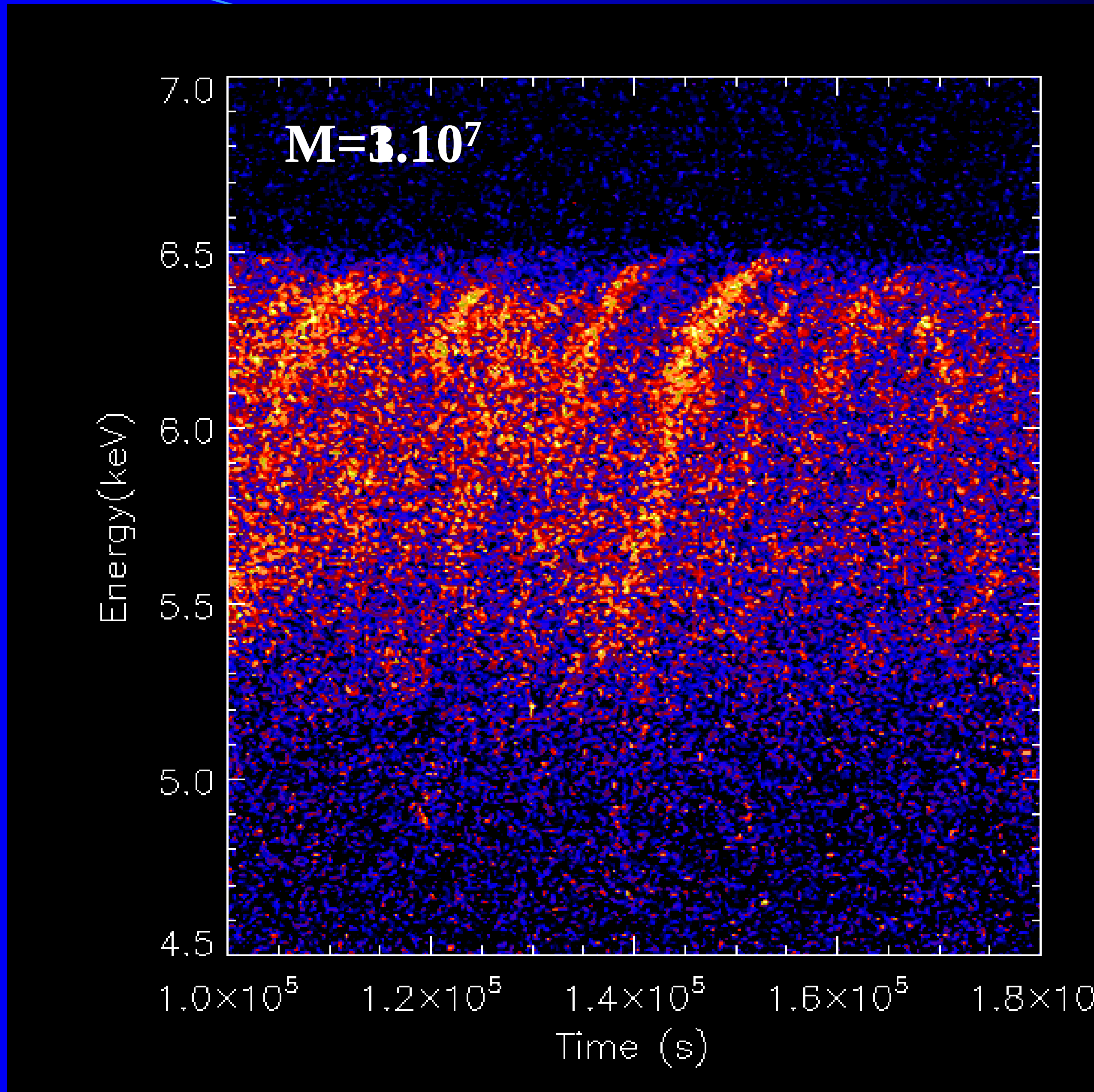
"Iron line hot spots" from

- orbiting coronal flares
- corrugations in disk surface
- patchy ionization structure

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.



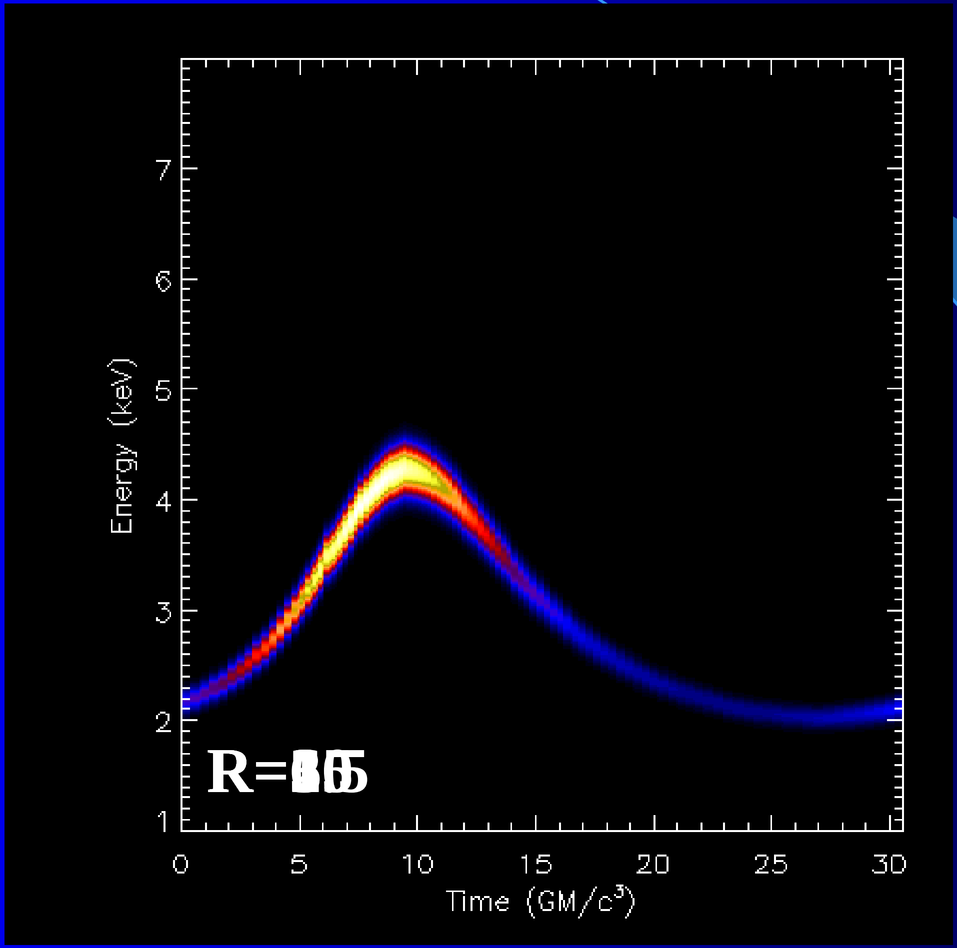
Arcs trace orbits of disk material around black hole… can be compared with predicted GR orbits



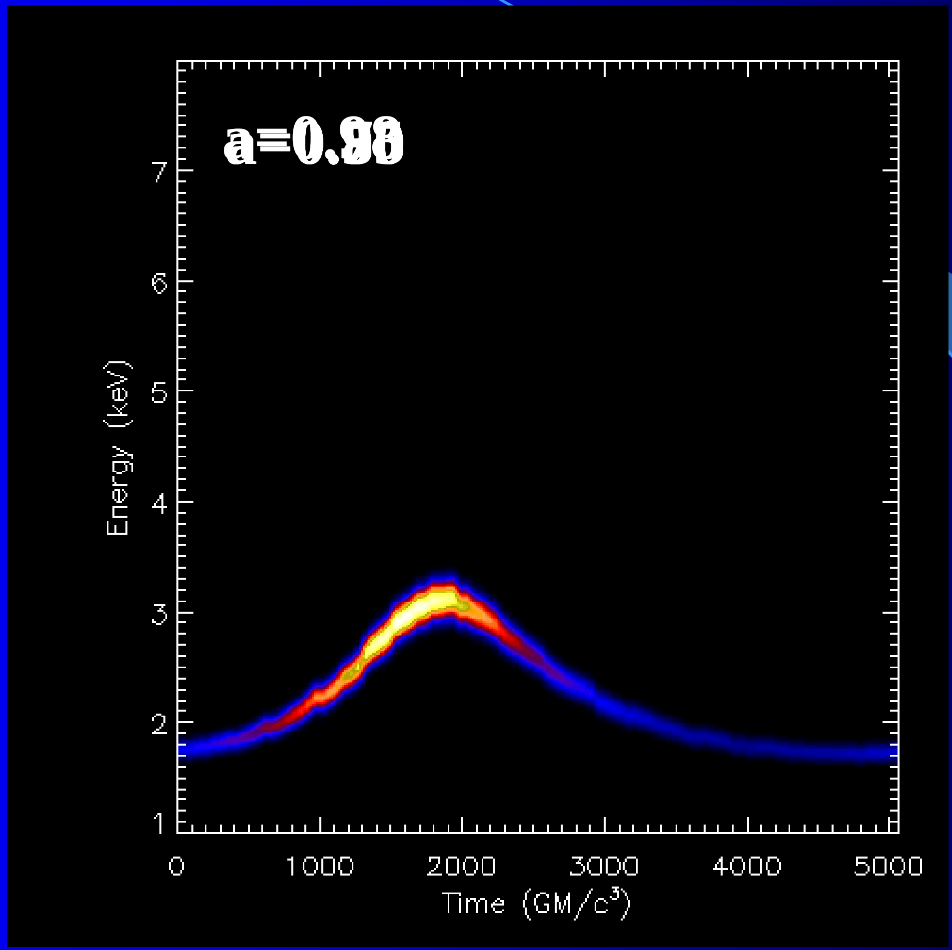
$M=3.10^7$
7.0
6.5
6.0
5.5
5.0
4.5
Energy(keV)
1.0×10^5
1.2×10^5
1.4×10^5
1.6×10^5
1.8×10^5
Time (s)

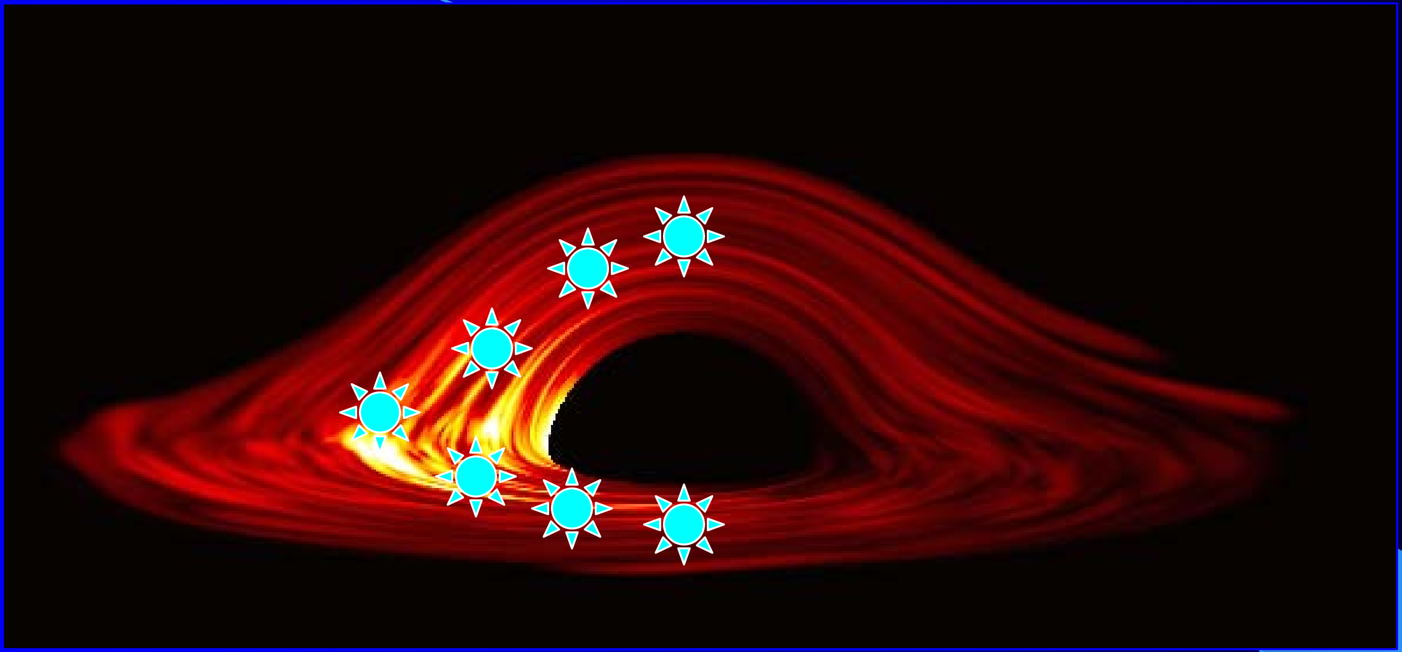
Keplerian orbit of a single "hot spot"

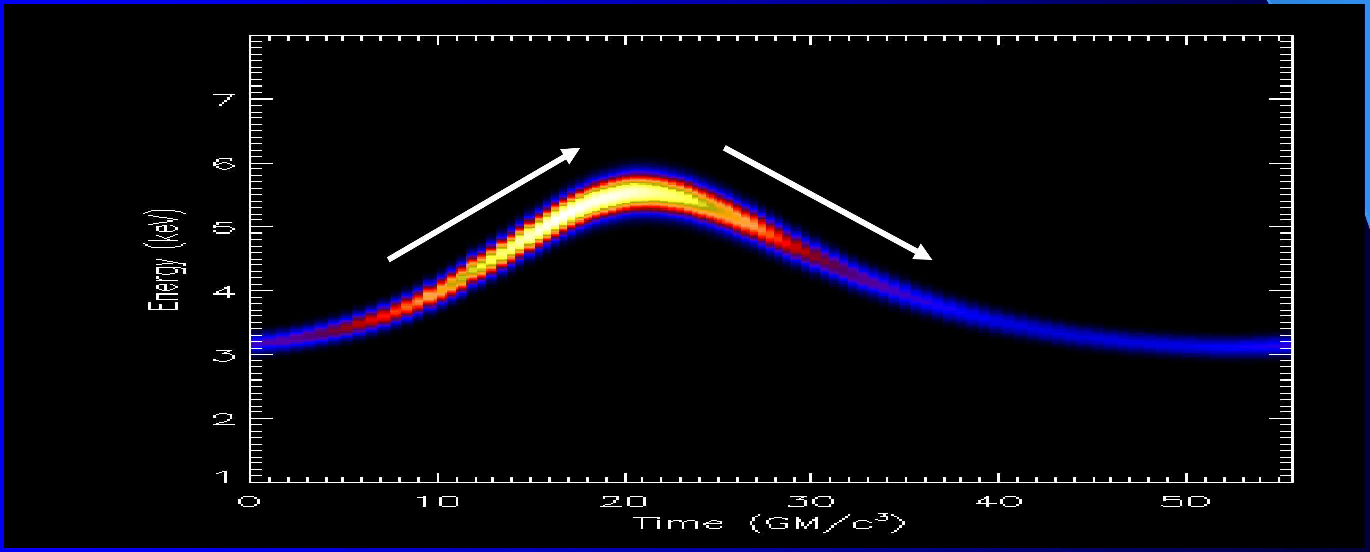
$a=0.98$
$i=30^{o}$



R=3.0
I=30

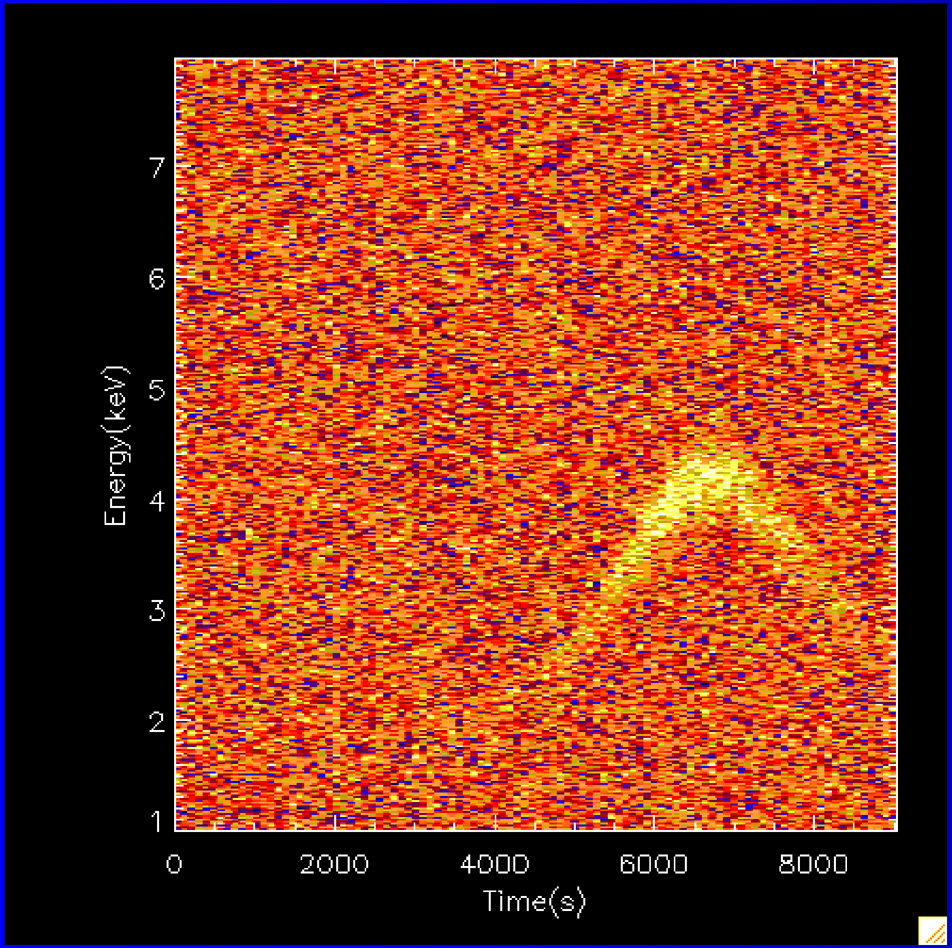


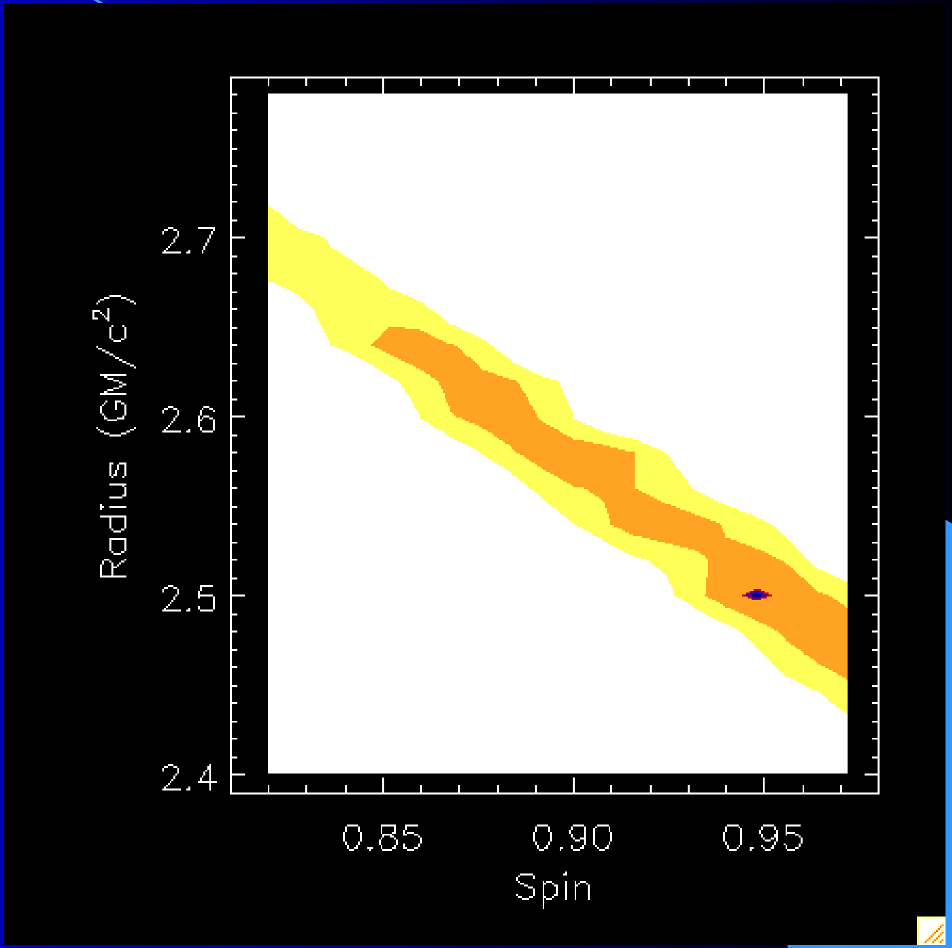




Energy (keV)
1
2
3
4
5
6
7
0
10
20
30
40
50
Time (GM/c³)

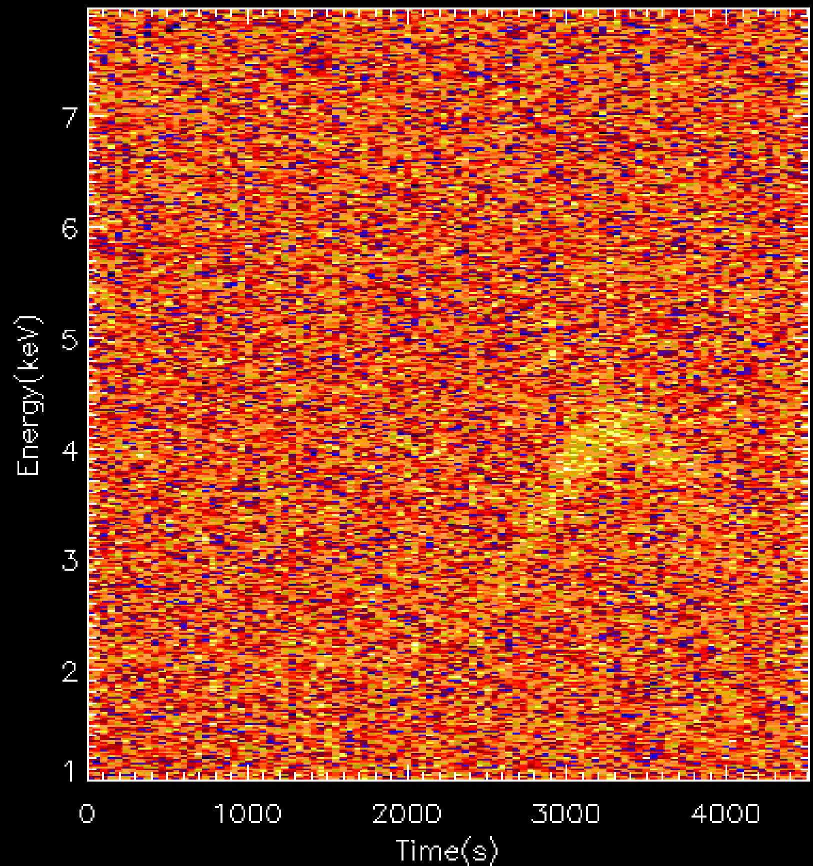
Con-X simulation of single blobs

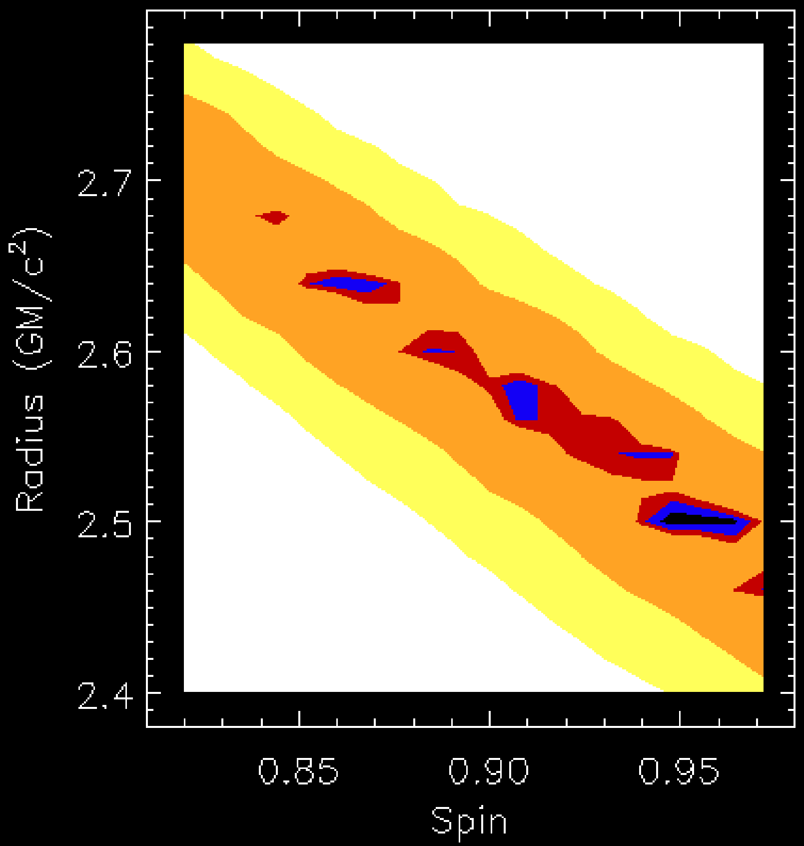




F=5×10^{-11} erg/s/cm2; EW=20eV; M=6×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

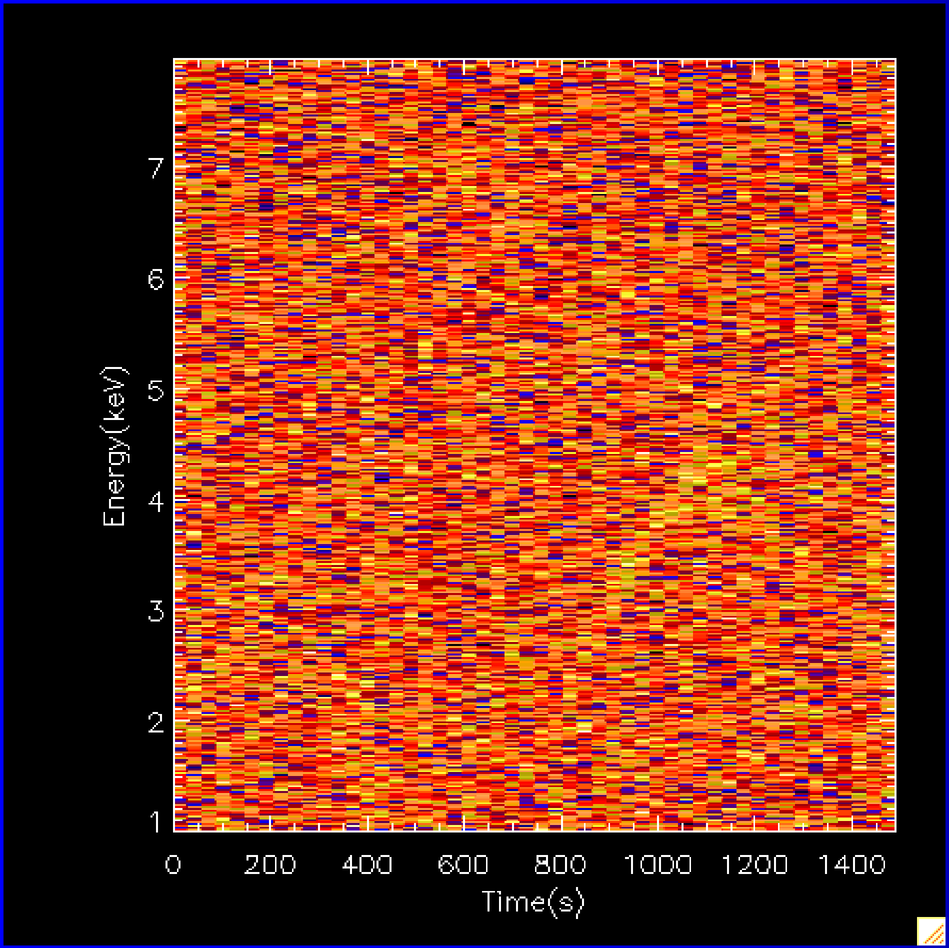
Con-X simulation of single blobs

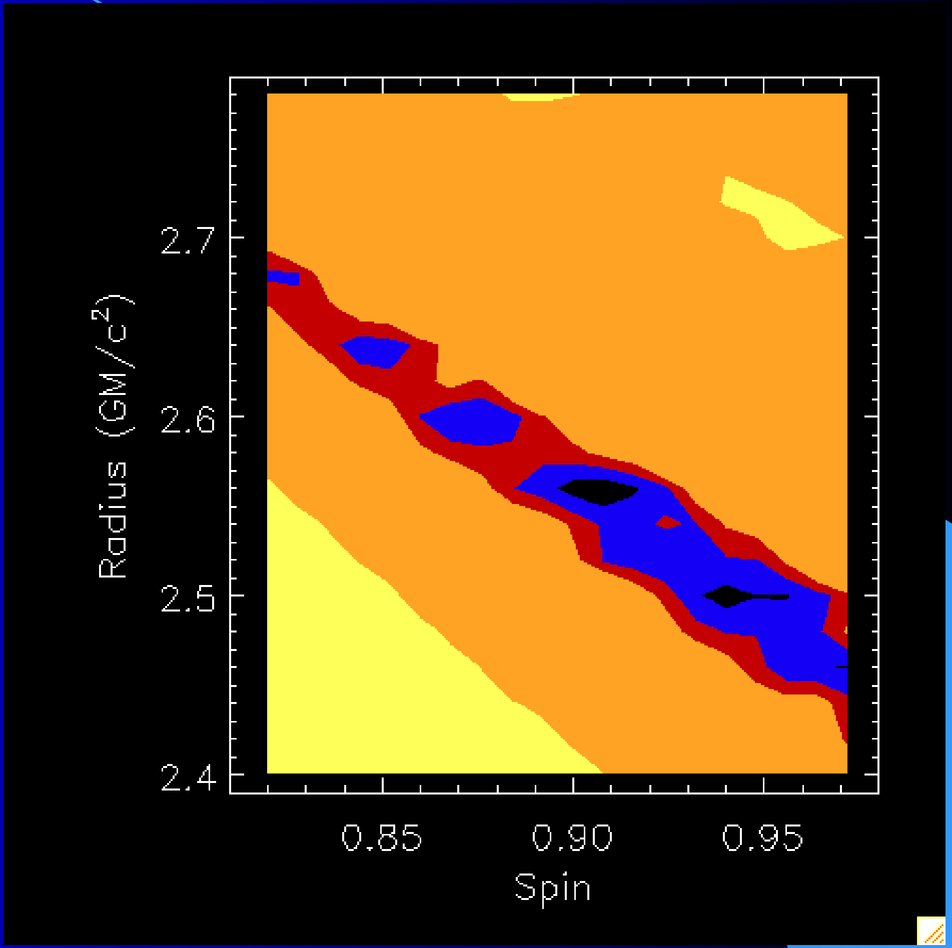




F=5×10^{-11} erg/s/cm2; EW=20eV; M=3×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

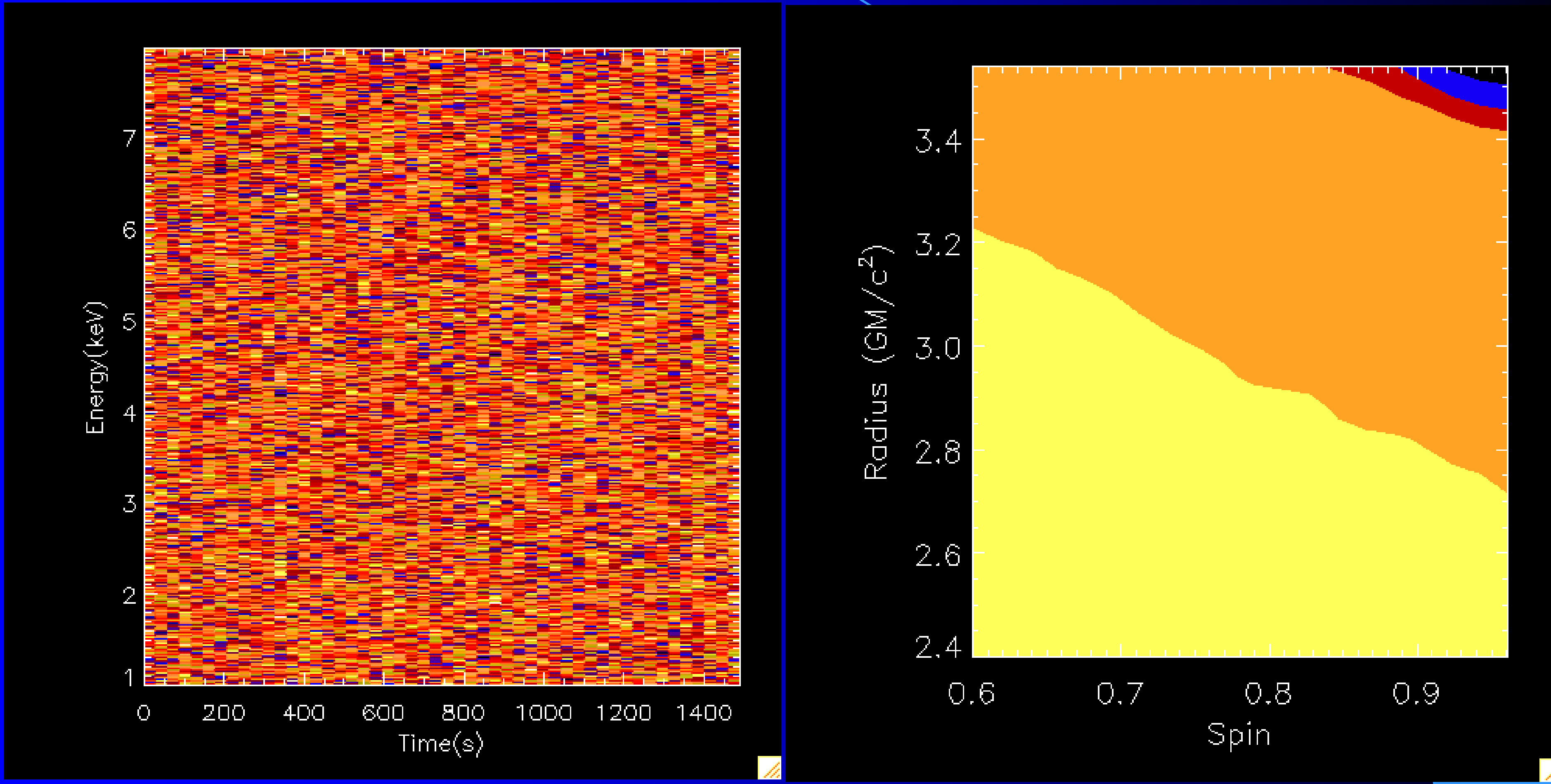
Con-X simulation of single blobs





F=5×10^{-11} erg/s/cm2; EW=20eV; M=1×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

Con-X simulation of single blobs



F=5×10^{-11} erg/s/cm2; EW=10eV; M=1×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

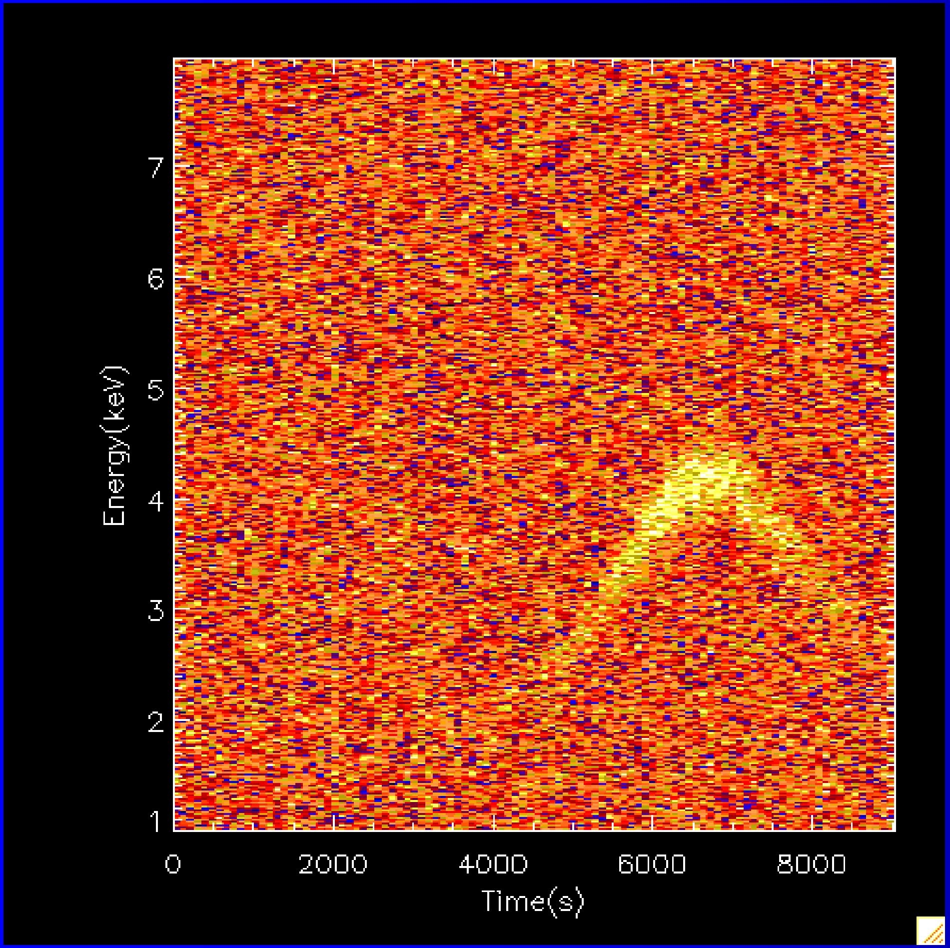
Scheme for testing GR

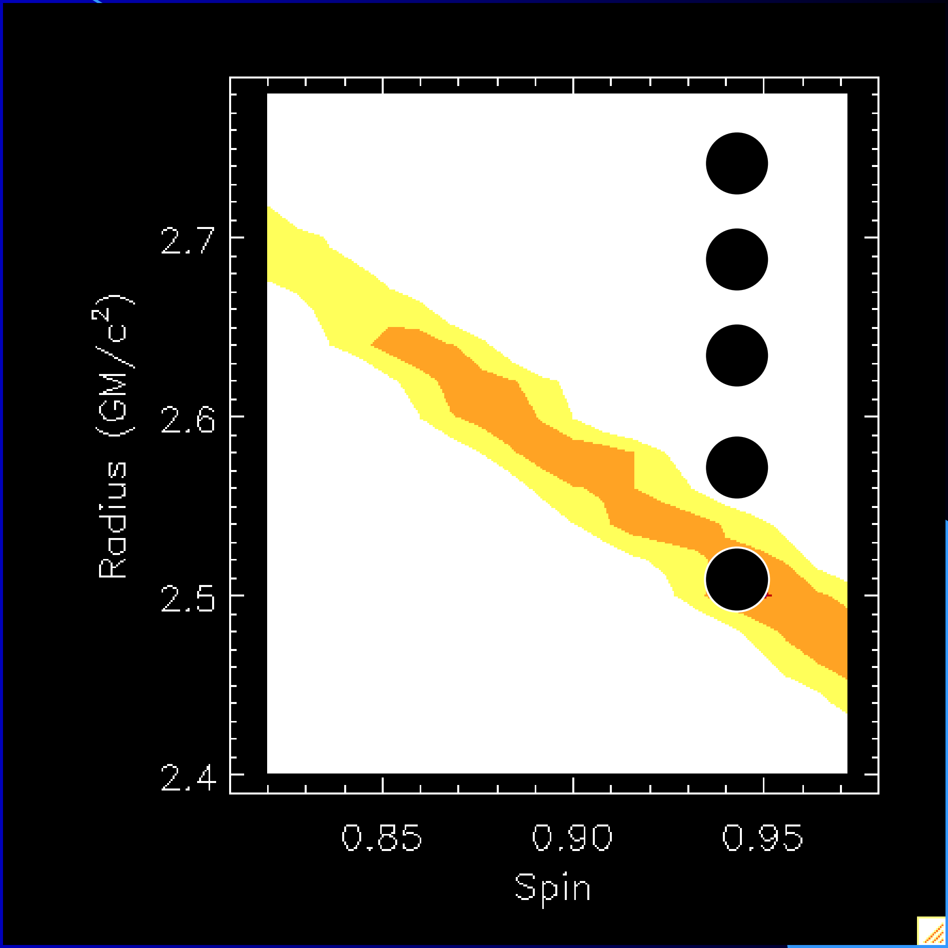
- Spin measurements are fundamentally measuring aspects of the spacetime metric

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right) dt^2 - \frac{4aMr\sin^2\theta}{\Sigma} dt\, d\phi + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2a^2Mr\sin^2\theta}{\Sigma}\right)\sin^2\theta d\phi^2$$

- From iron line tracks, we can measure a spin at a number of different radii (assuming GR)…
  - Powerful consistency check… inferred spin had better be independent of radius
  - Many deviations from GR would produce a radial dependence on the inferred spin

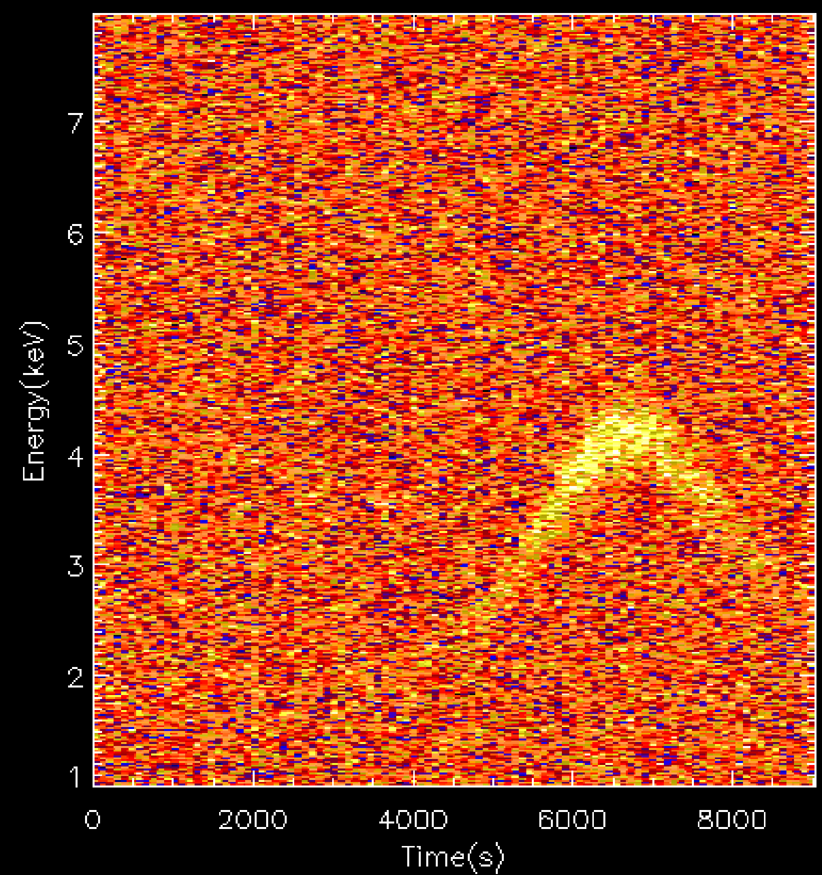
Con-X simulation of single blobs

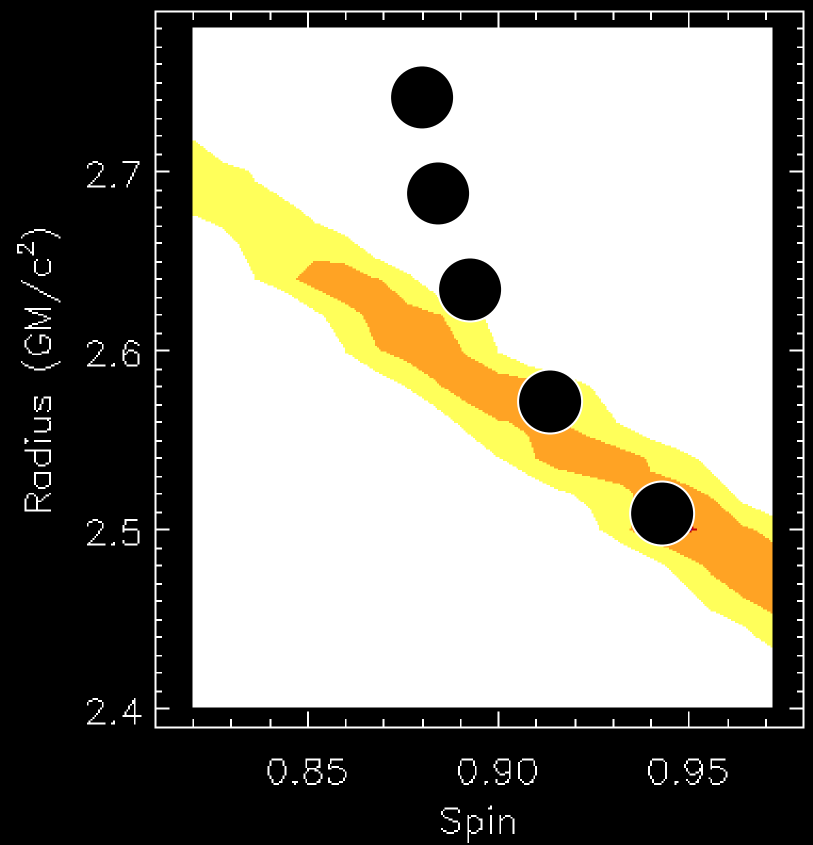




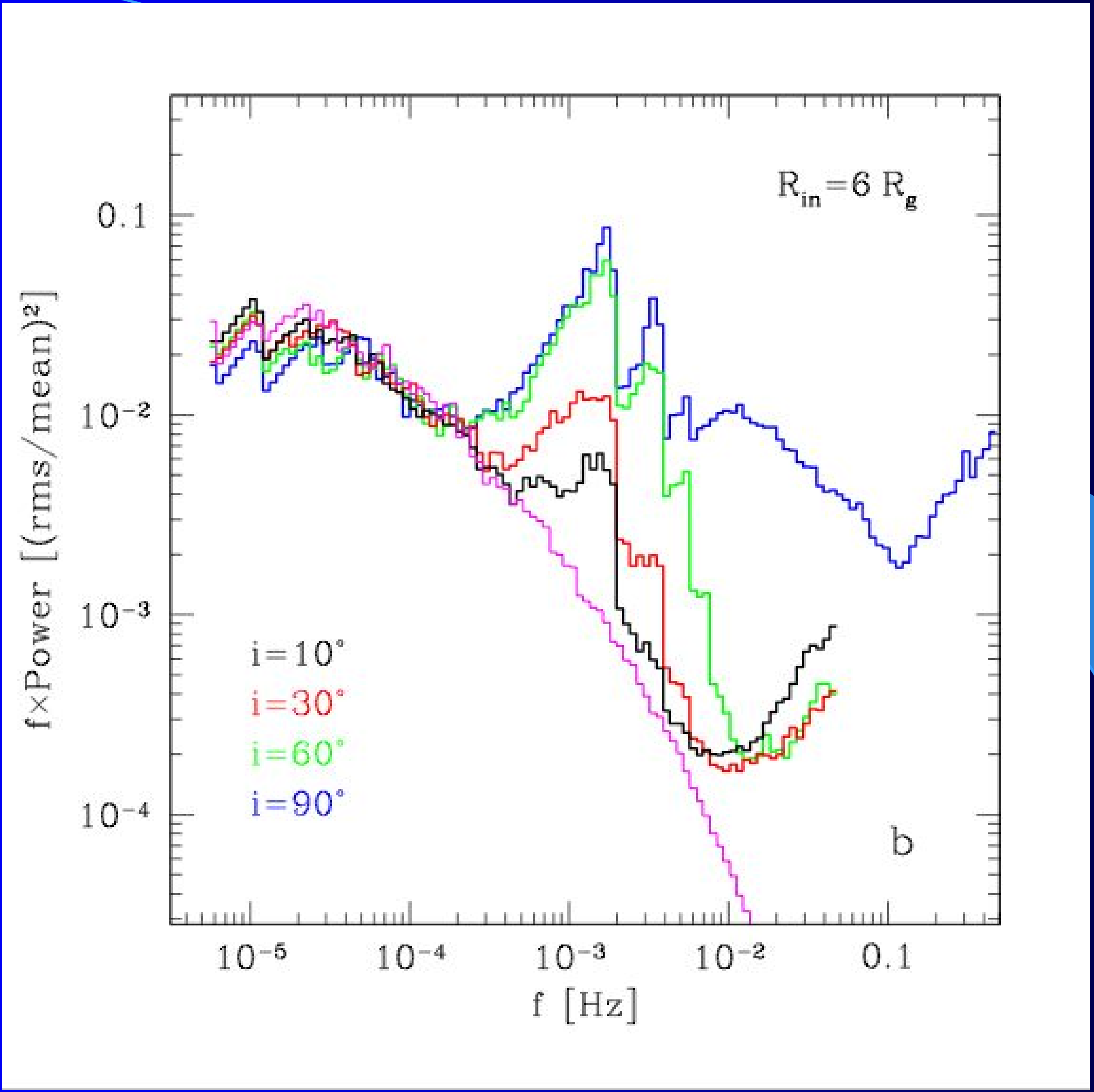
$F=5\times10^{-11}$ erg/s/cm2; EW=20eV; $M=6\times10^{7}$
r=2.5 ; a=0.95 ; i=30 degrees

Con-X simulation of single blobs

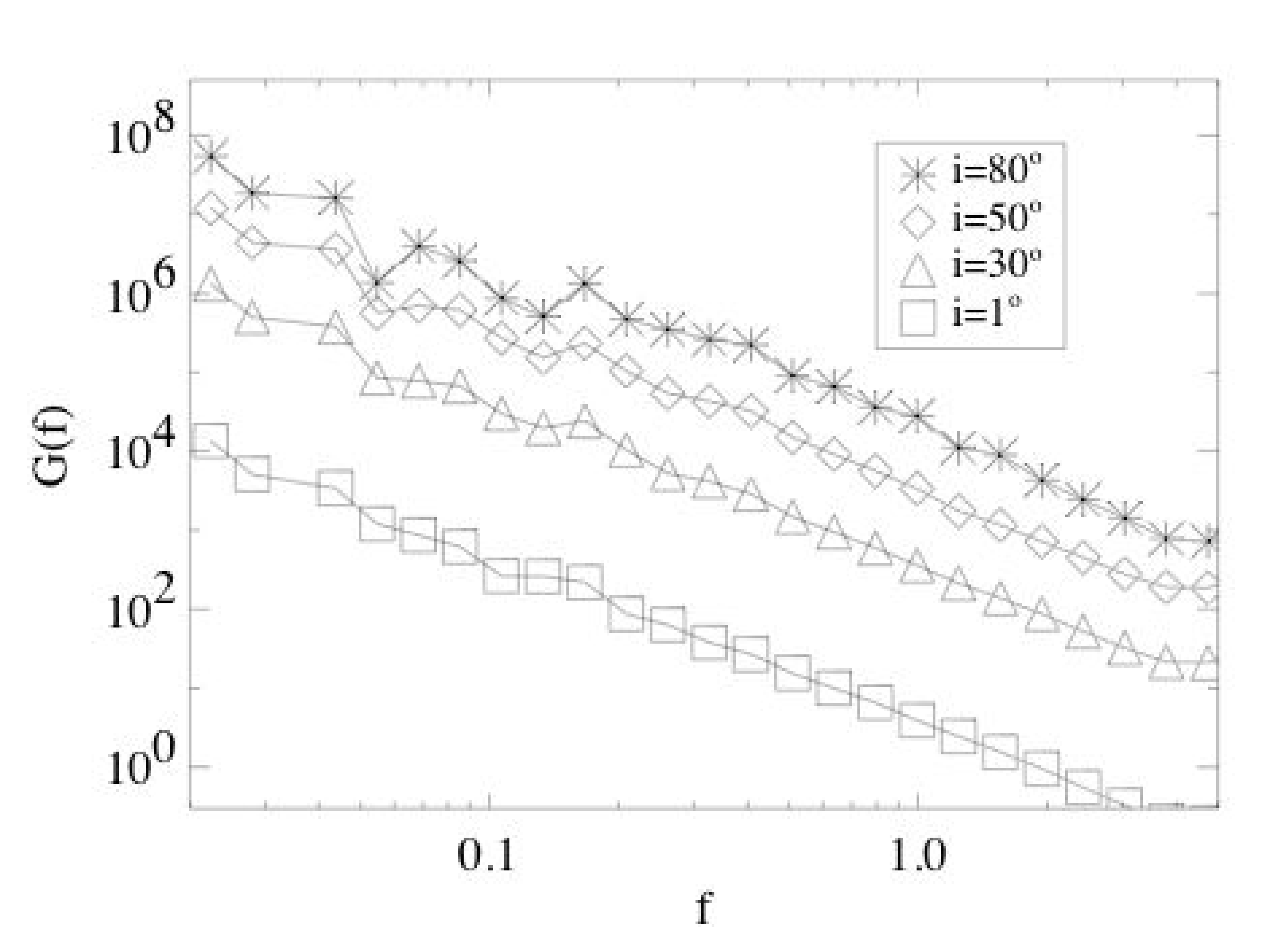




F=5×10^{-11} erg/s/cm2; EW=20eV; M=6×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

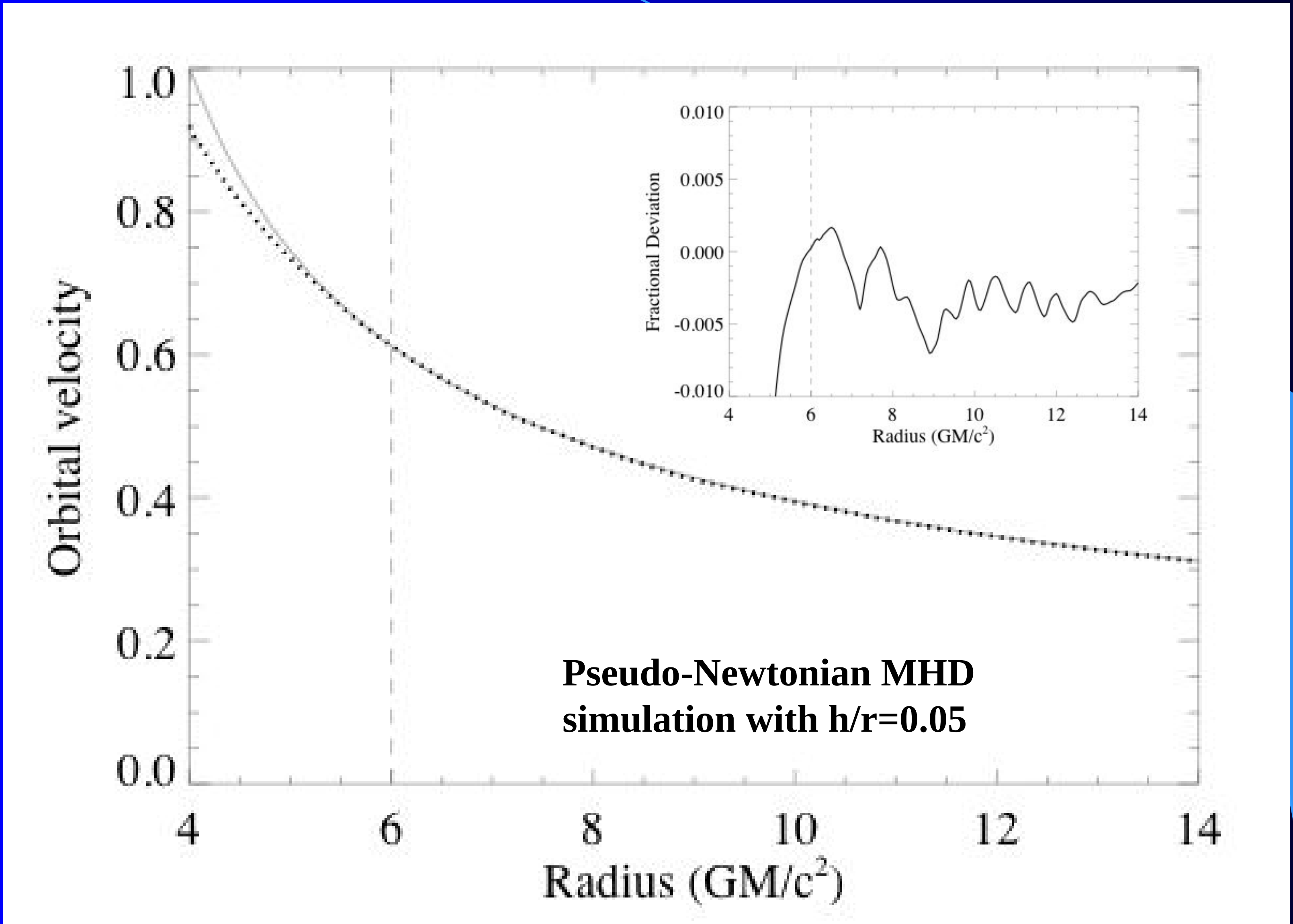


Power spectra from a phenomenological flare model
Zycki & Niedzwiecki (2005)

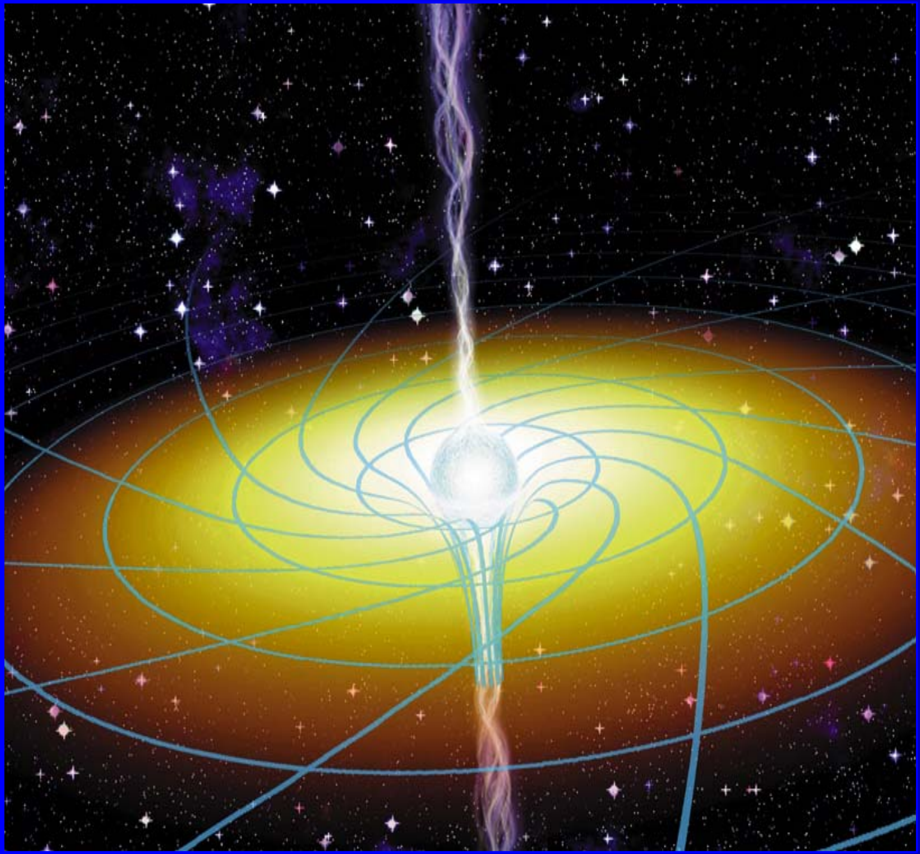


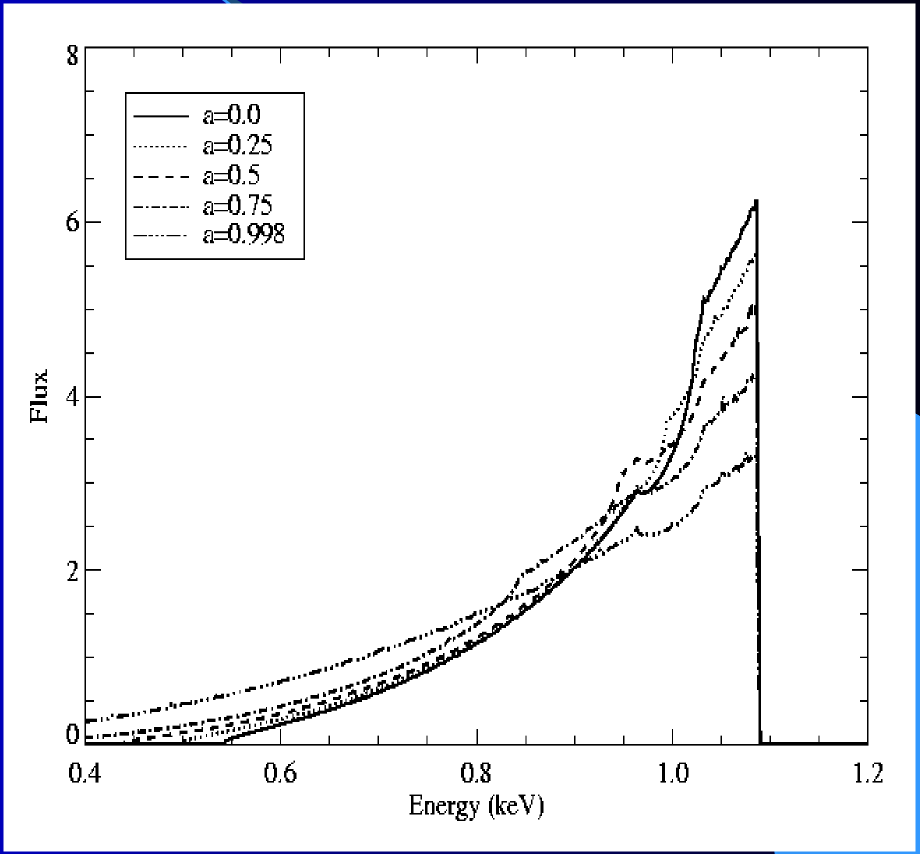
Power spectra from MHD simulation including relativistic photon propagation effects (Armitage & CSR 2003)

Comparison of simulated accretion flow with test-particle orbits…

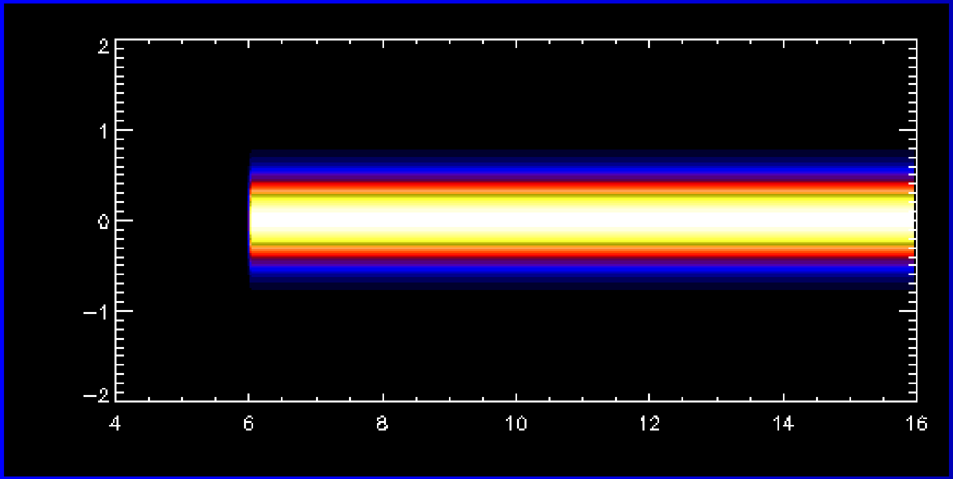


II : Probing Black Hole Spin

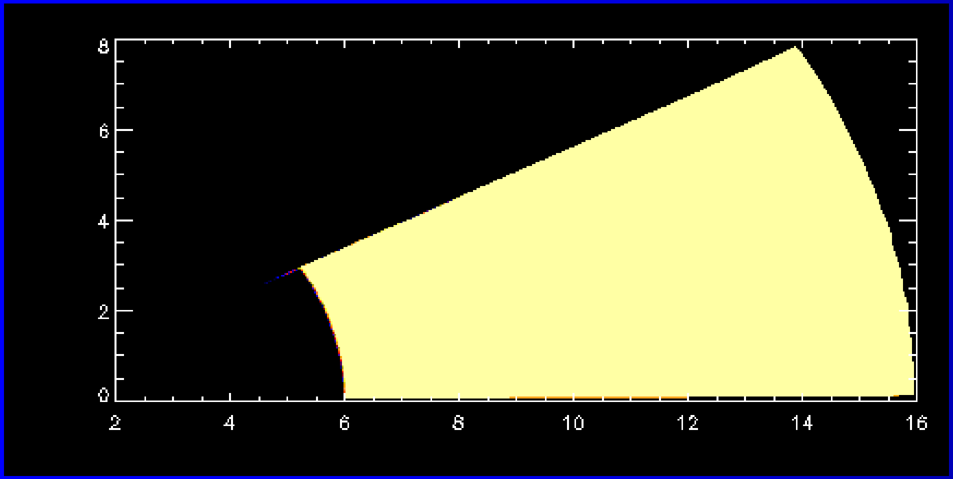


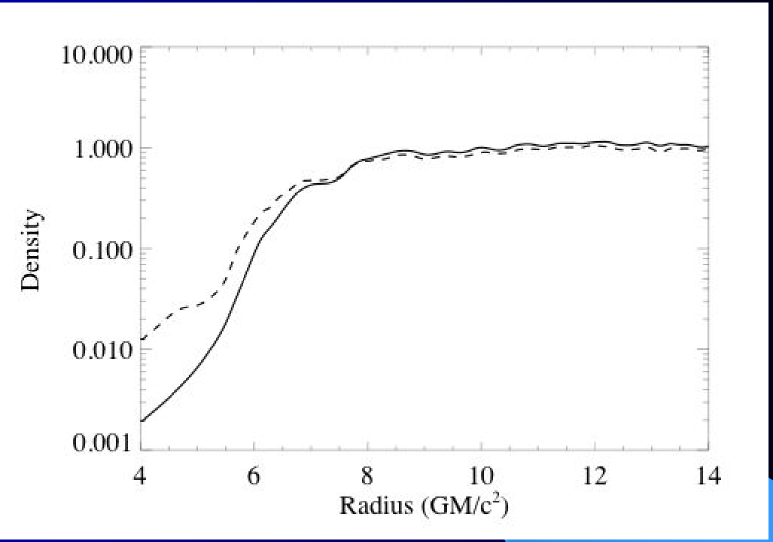


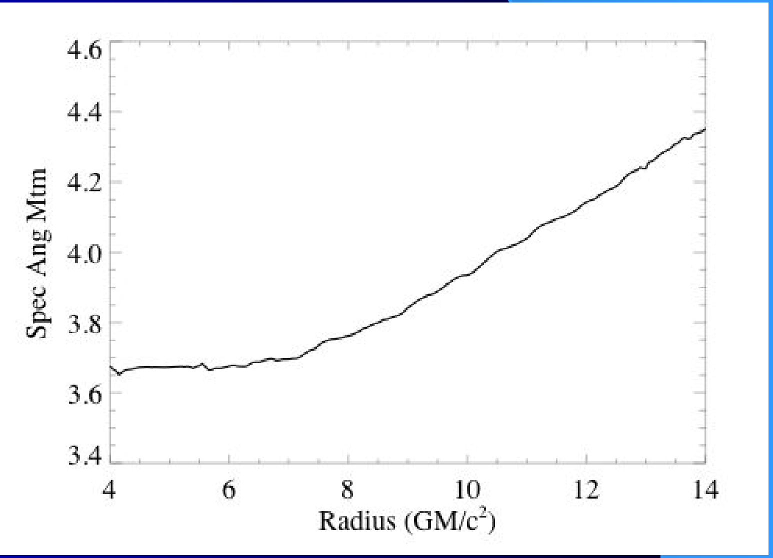
Relevance of ISCO confirmed by MHD simulations of thin disks (at least for low-spins)

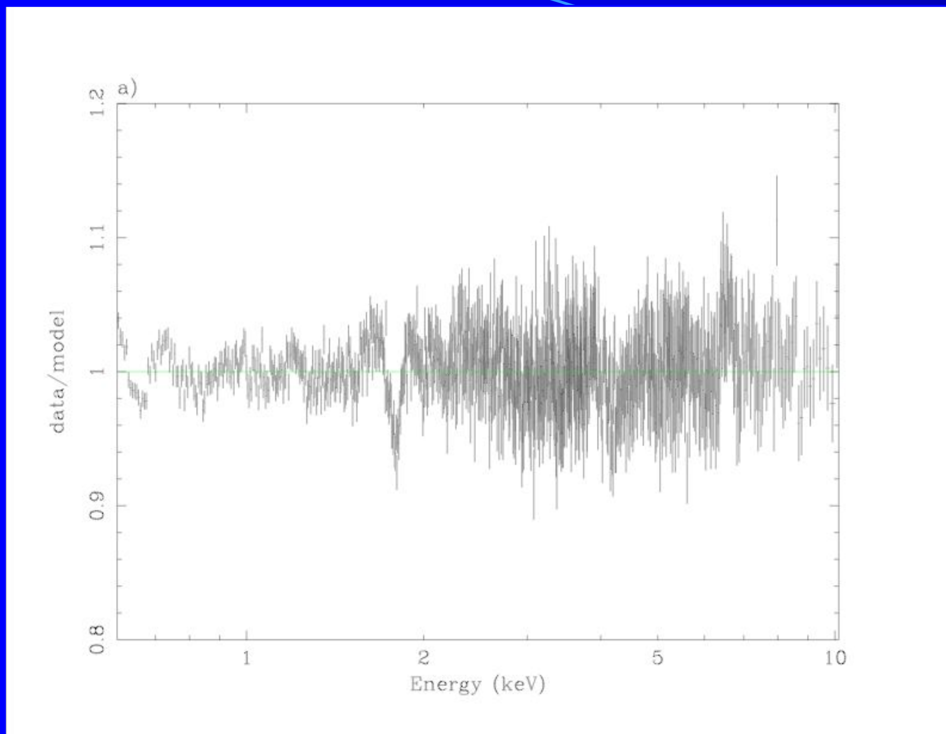


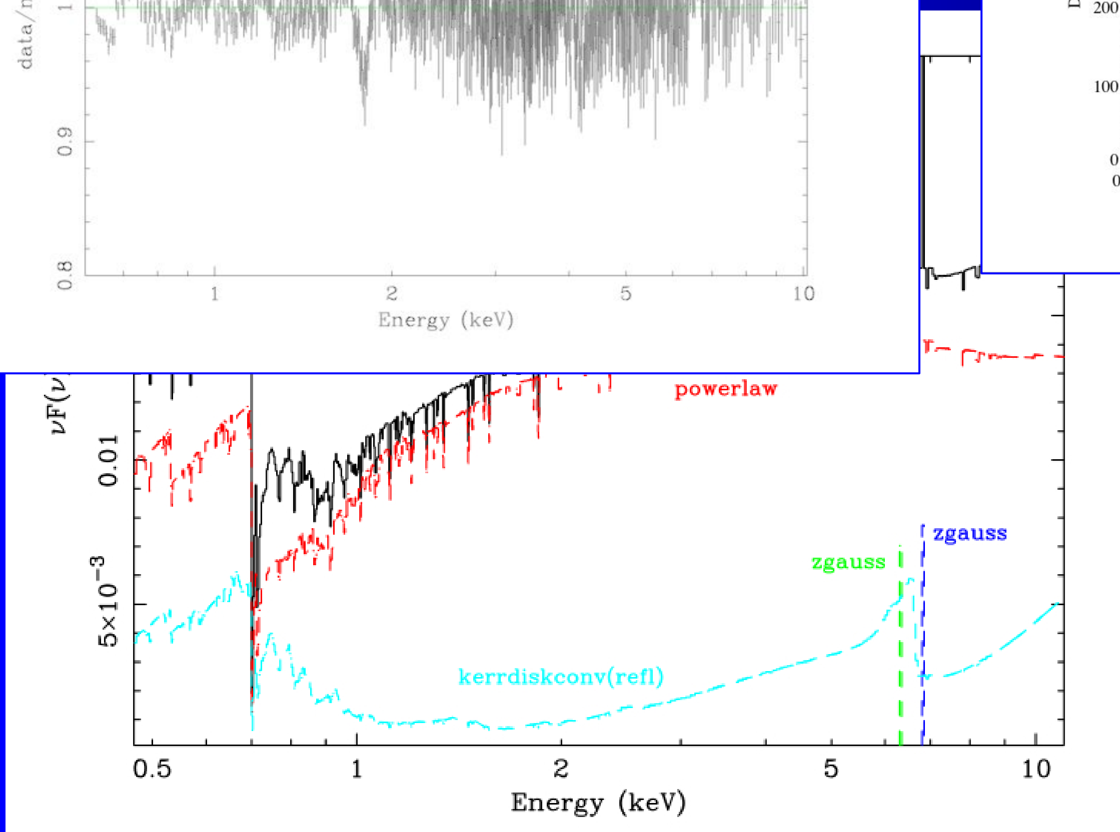
$$\Phi = \frac{GM}{R - 2GM/c^2}$$

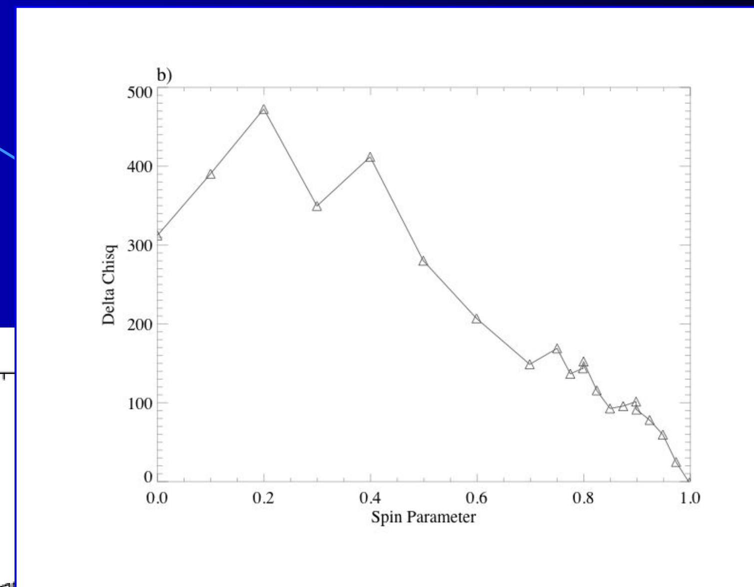










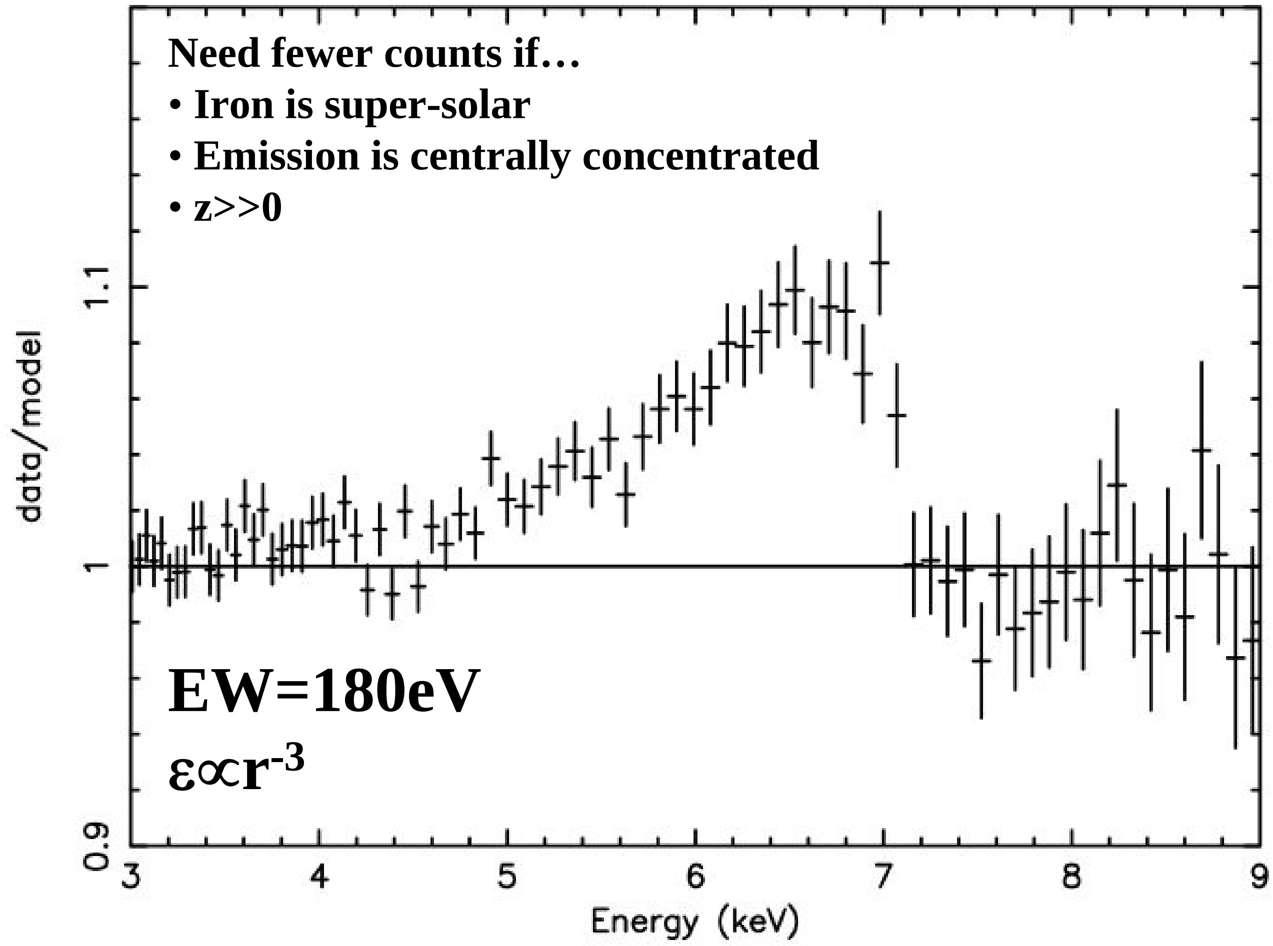


Formal 90% confidence limit of a>0.987

Brenneman & Reynolds (2006)

Constellation-X simulation

1 million 2-10keV photons; constrains a>0.90 for a_{model}=0.95



2-10keV count rate of 13cps for a F_{2-10}=10^{-11}erg/s/cm^2

In how many AGN can we measure spin?

- Strategy : target known AGN on the basis of flux and the presence of a broad iron line… “run down the log N - log S curve”
- Canonical parameters…
  - Need $n_{ph}=10^6$ 2-10keV photons to determine spin to 10% accuracy
  - Assume f=0.5 of sources possess broad iron line
  - Suppose we devote 10Ms to spin measurements
- Using HEAO-A1 LogN-LogS…

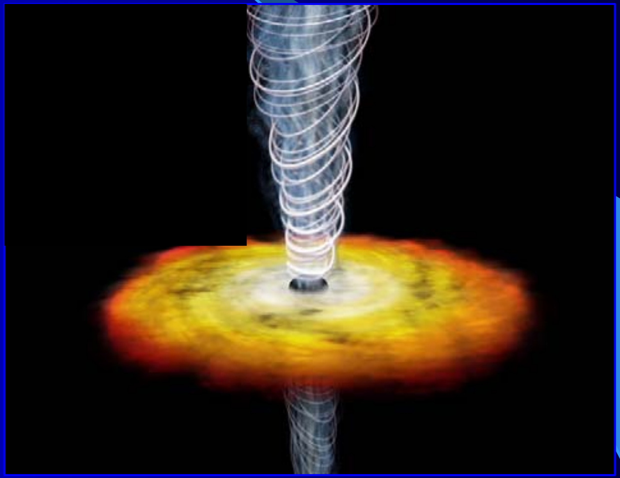
$$N_{tot} \approx 140 \left(\frac{f}{0.5}\right)^{2/5} \left(\frac{n_{ph}}{10^6}\right)^{-3/5} \left(\frac{\Omega}{3\pi}\right) \left(\frac{T}{10^7\ s}\right)^{3/5}$$

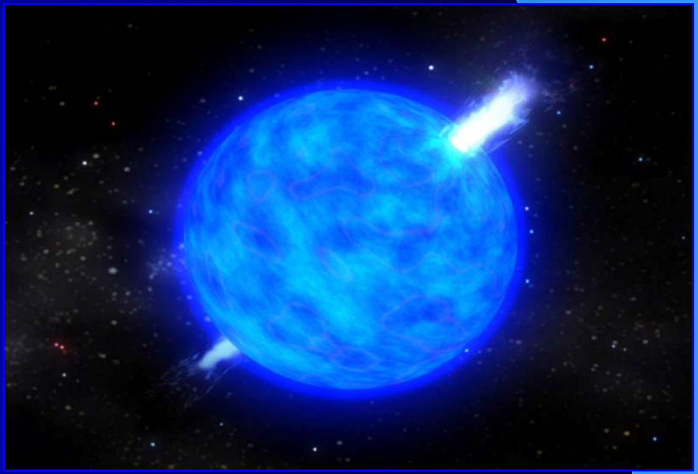
- Need precusor survey to identify those sources with broad iron lines
  - Con-X can obtain sufficient s/n on brightest 500+ AGN in 10Ms
  - Some fraction of this precusor work will be conducted by XMM and Suzaku beforehand

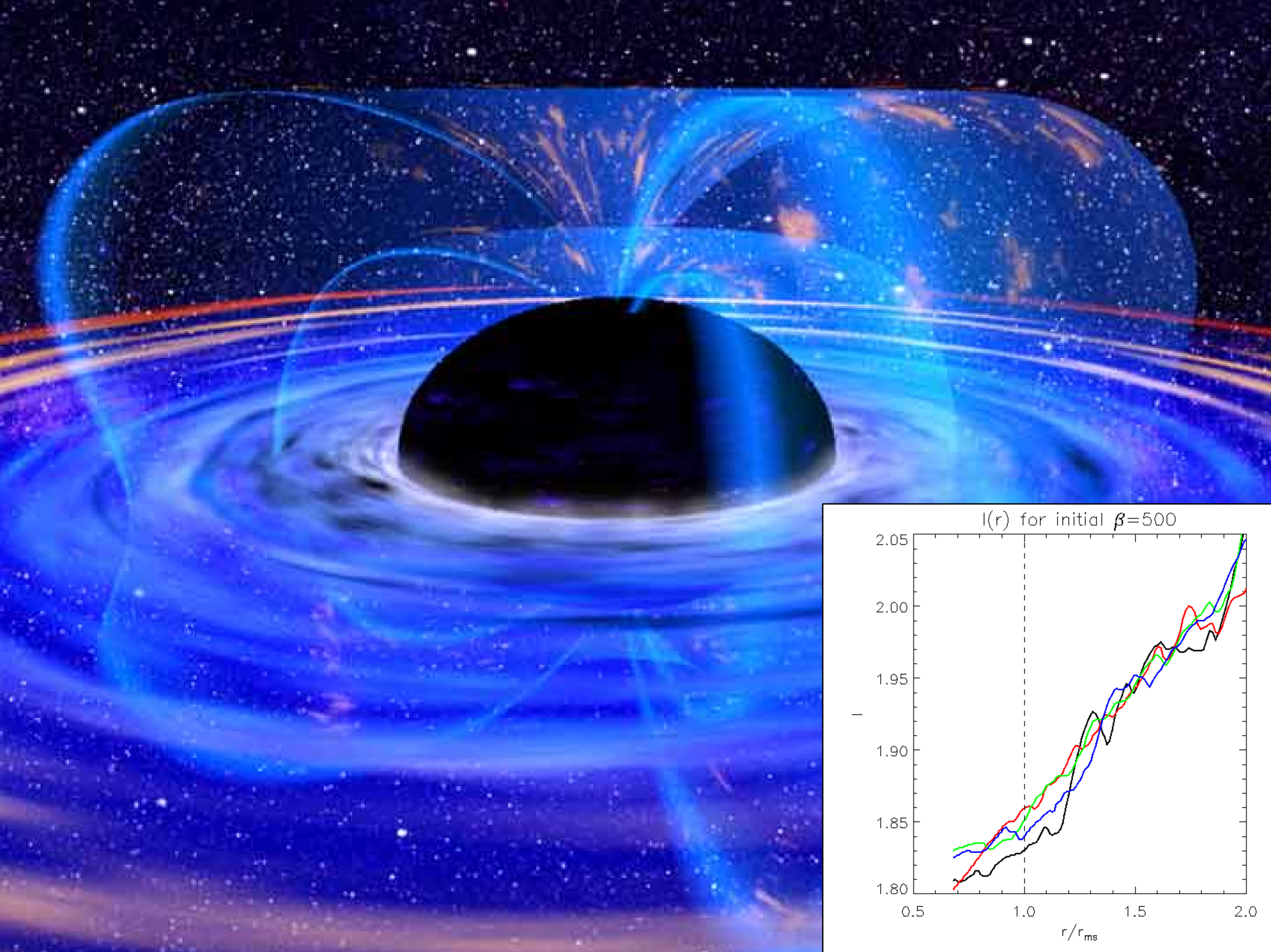
Why do we care about spin?

- Spinning black holes are potentially powerful energy source
  - Drive relativistic outflows/jets (Blandford-Znajek effect)
  - Enhance dissipation in inner regions of accretion disk
  - High-energy particle acceleration

- Spin encodes formation and evolution of the black hole
  - Natal spins in stellar-mass BHs… probe formation event
  - Probe accretion/merger history in AGN

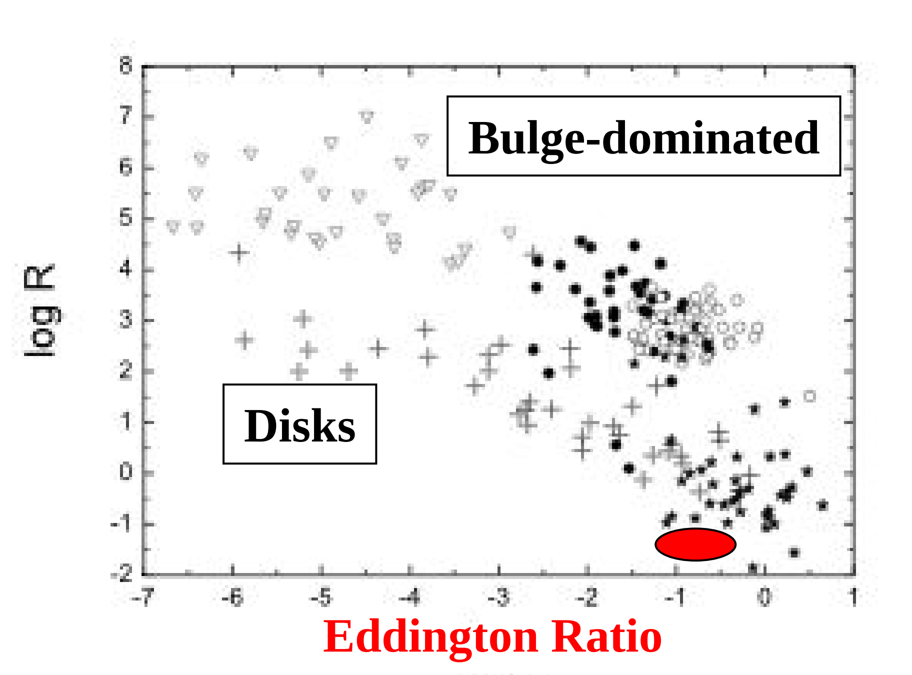





l(r) for initial β=500
2.05
2.00
1.95
1.90
1.85
1.80
0.5
1.0
1.5
2.0
r/r_ms

The "spin paradigm" of AGN

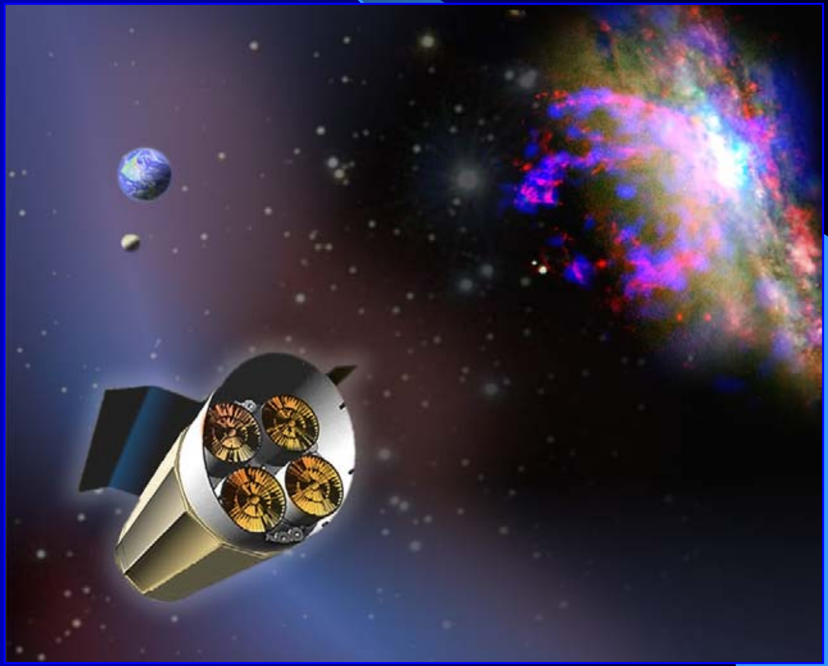
- What underlies the radio-loud /radio-quiet dichotomy?
- Revised Spin Paradigm
  - AGN radio loudness determined by spin and Mdot
  - Rapid BH spin is necessary but not sufficient for powerful jets
  - Postulate that bulge-dominated galaxies have higher-spin than disk dominated
  - Low-Mdot… spin powered jet
  - High-Mdot… jet quenched
- MCG-6 already suggests breakdown of this hypothesis



Sikora, Stawarz & Lasota (2006)

Constellation-X “Key Projects”

- Con-X Strong Gravity Project
  - Use iron line variability in brightest ~10 AGN to probe Kerr metric
- Con-X Spin Survey (10Ms)
  - Measure black hole spin in 150-300 AGN
- Con-X AGN Survey (precusor)
  - Observe brightest 500+ AGN in 2-10keV sky (<10Ms)
  - Identify all objects with relativistic iron lines

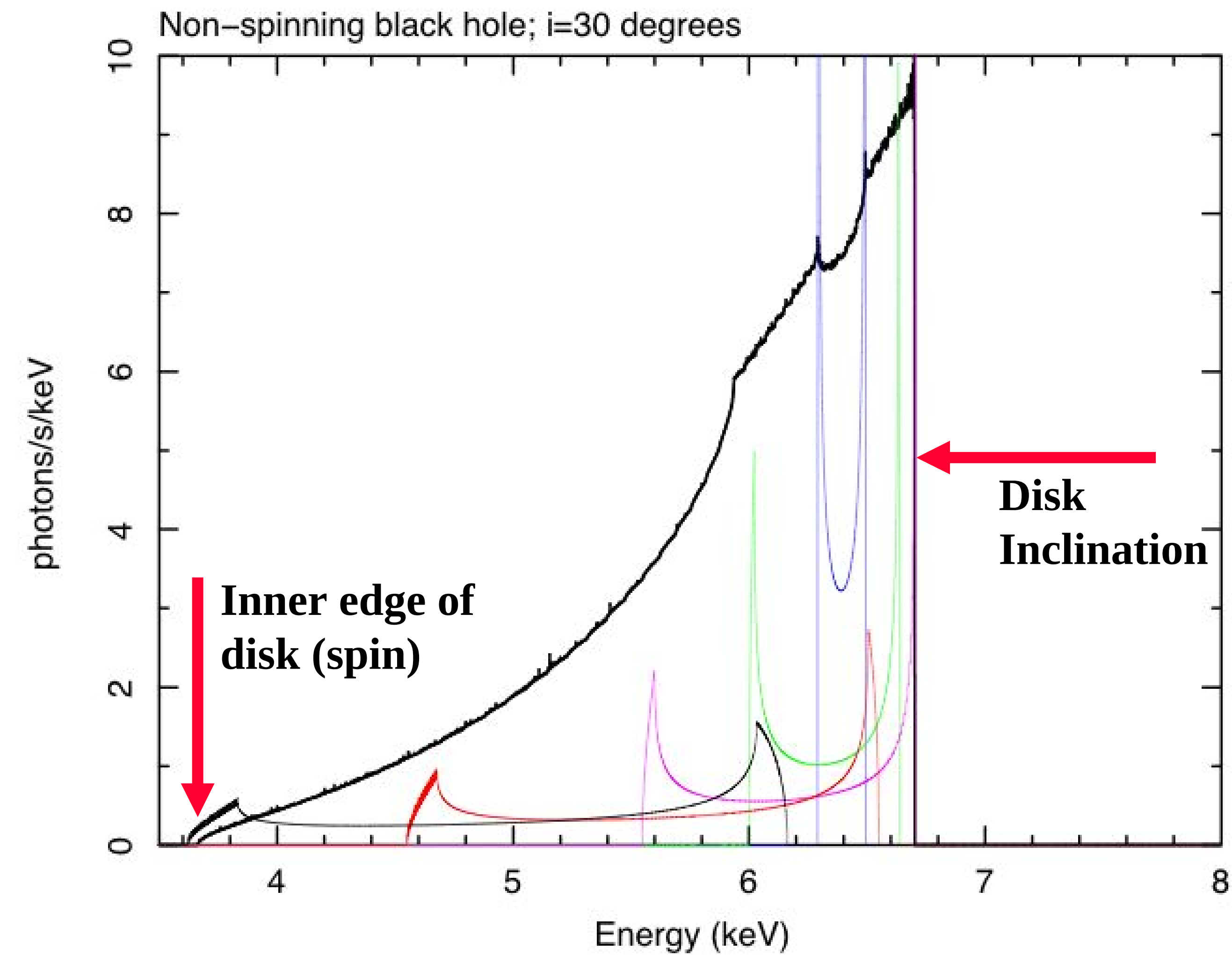


Beyond supermassive black holes… spanning the mass scales

- Can measure spins in stellar mass, intermediate mass, and super-massive black holes!
  - Time-averaged iron line profiles are insensitive to mass (consequence of scale invariance of GR)
- Constrain mass function of IMBHs from modeling thermal disk radiation
  - Compare with predictions for stellat-cluster core collapse, Pop-III remnants and/or primodial BHs
- Constrain “large” scale extra dimensions from life-time of stellar-mass black holes
  - Age constraints (e.g., from Con-X studies of mass transfer) translate into constraints on size of extra dimension [due to increased Hawking evaporation]

Conclusions

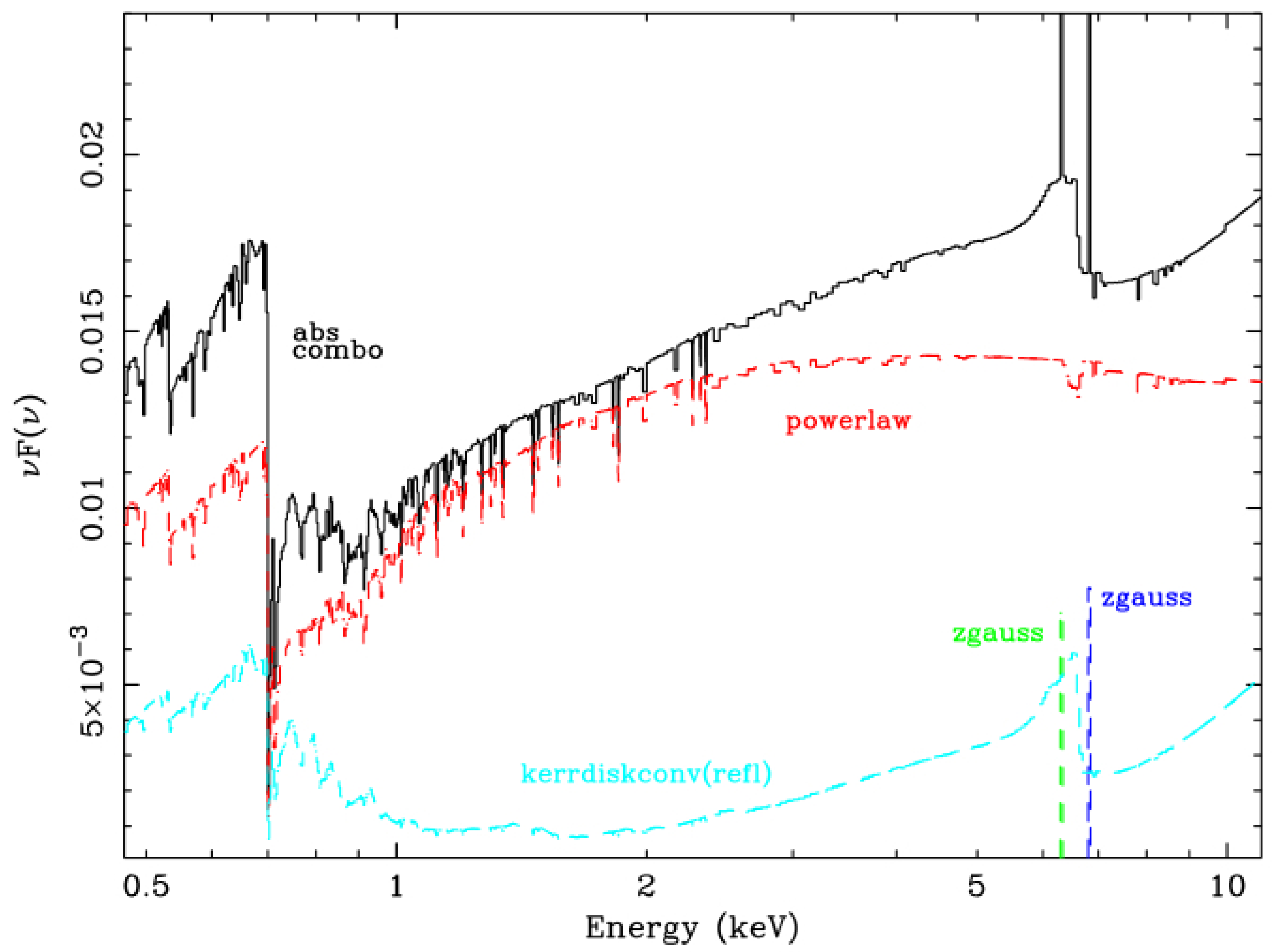
- Constellation-X enables extremely exciting black hole and strong gravity studies!
- Orbital iron line variability
  - Even low s/n tracks provide good constraints on radius and spin
  - Probe for deviations of GR from radial dependence of inferred spin parameter
- Constellation-X Spin Survey
  - Can measure spin in 150-300 AGN in 10Ms
  - Open up astrophysics of BH spin for the first time
  - Need precusor survey to identify broad line sources



Non−spinning black hole; i=30 degrees
photons/s/keV
Energy (keV)
0
2
4
6
8
10
4
5
6
7
8
Inner edge of disk (spin)
Disk Inclination

Assessment of constraints from orbiting blobs (Chris Reynolds & Cole Miller)

- Current status
  - Constructed libraries of orbital tracks
  - Constructed "single blob" Con-X simulations
  - Developed simple (grid-search) fitting algorithm.
  - Obtain extremely good constraints from even moderate s/n tracks (r, a, phase, norm as free parameters; *assuming known mass & inclination*).
- Future work
  - More sophisticated fitting algorithms (MCMC).
  - Assess spin constraints as function of radius, mass, flux
  - Explicit demonstration of multiple track decomposition



Brenneman & Reynolds (2006)